J. Plasma Fusion Res. SERIES, Vol. 5 (2002) 328–332

Investigation of Turbulence in High-Temperature Plasma by Microwave Scattering Techniques in Modern Stellarators

SKVORTSOVA Nina N., BATANOV German M., KOLIK Leonid V., PETROV Alexander E., PSHENICHNIKOV Anton A., SARKSYAN Karen A., KHARCHEV Nikolay K., OHKUBO Kunizo[1], SHIMOZUMA Takashi[1], IDEI Hiroshi[1], YOSHIMURA Yasuo[1], KUBO Shin[1], SANCHEZ Joaquin[2], ESTRADA Tereza[2] and VAN MILLIGEN Boudewijn[2]

General Physics Institute, Moscow 117942, Russia

[1] National Institute for Fusion Science, Toki 509-5292, Japan

[2] EUROATOM-CIEMAT, Madrid 28040, Spain

(Received: 12 December 2001 / Accepted: 19 July 2002)

Abstract

One of the problems of plasma turbulence is the complexity of experimental investigations of fluctuations in the central region of the plasma column. The development of diagnostics that make it possible to directly measure fluctuations of plasma parameters in the plasma core is of great importance. A description of such diagnostics is given in this article, along with results from the first measurements of the characteristics of fluctuations in high-temperature plasmas in three essentially different helical systems: L-2M (GPI, Moscow), LHD (NIFS, Toki), and TJ-II (CIEMAT, Madrid).

Keywords:

plasma turbulence, stellarator, microwave, scattering technique

1. Introduction

The study and description of the spectral and probability characteristics of random plasma processes has long attracted the attention of investigators engaged in the field of plasma physics. Recently, interest in this problem even has increased when it became clear that many global plasma processes (diffusion of particles, heat conductivity, equilibrium in the magnetic field, etc.), depend large on random fluctuation of a number of plasma variables [1,2]. Therefore, information on spectral and probability behavior of fluctuations is of prime importance for solving fundamental and applied problems related to the creation of high-temperature plasma in thermonuclear toroidal devices. To date, the probability and spectral characteristics of fluctuations in the region of toroidal devices in which a low-temperature plasma exists (the edge of the plasma column) has been studied in sufficient detail. Diagnostic techniques for measuring the characteristics of fluctuations in the edge plasma are available in every toroidal device (both in stellarators and tokamaks); because of this, the behavior of fluctuations at the plasma edge is studied extensively. As a rule, the density fluctuations in a low-temperature plasma are described by the model of strong structural turbulence [3,4]. The temperature and density in the central region of the plasma column are two orders of magnitude higher than those at the edge. Study of fluctuation processes in this region is much more interesting, but more complicated problem because adequate diagnostic techniques are lacking. In recent times investigation of plasma center fluctuations began by the very complicated HIB diagnostic [2]. An original and simpler

Corresponding author's e-mail: nina@fpl.gpi.ru

method of measuring the characteristics of density fluctuations in high-temperature plasma was elaborated in the General Physics Institute. This method based on microwave scattering on fluctuations provides information on the behavior of fluctuations in the central plasma region.

2. Scattering Experiment in the L-2M Stellarator

The basic parameters of the L-2M stellarator are described in detail in ref. [5]. The major radius is R = 100 cm, and the mean vacuum separatrix radius is r_s = 11.5 cm.

The plasma was created and heated with a gyrotron operating at a frequency of f_0 = 75 GHz ($\lambda_0 \approx$ 4 mm). The plasma parameters in these experiments were the following: the mean plasma density was n = (1–2) × $10^{19}\ m^{-3}$, $T_e(0)$ ~ 0.5–0.7 keV, T_i ~ 0.15 keV. Density fluctuations δn in the plasma core were measured with a homodyne setup extracting a scattered signal from the heating gyrotron radiation. The setup detected the radiation arising from scattering of the ordinary component of high-power gyrotron radiation ($E_{ord} \parallel \boldsymbol{B}$, where $\boldsymbol{B}$ is the stellarator toroidal magnetic field) resulting from splitting of the linearly polarized radiation at the plasma boundary. The arrangement of the diagnostics in the poloidal cross section of the stellarator chamber is shown schematically in Fig. 1. A horn antenna that was positioned in the upper port received the ordinary component of the gyrotron radiation scattered at an angle of π/2 by density fluctuations from the central region of the plasma. This region (which is indicated in Fig. 1 by small squares) is the intersection region of the incident and scattered microwave beams. The diameter of the scattering region is d = 5 cm. For a wave number of gyrotron radiation k_0 = 15 cm^{-1}, the Bragg condition for scattering at an angle of p/2 is satisfied for the density fluctuations dn whose size corresponds to k_{sc} = 20 cm^{-1} (λ_{sc} = 3–4 mm). Fluctuations in the edge plasma were measured by Langmuir probes.

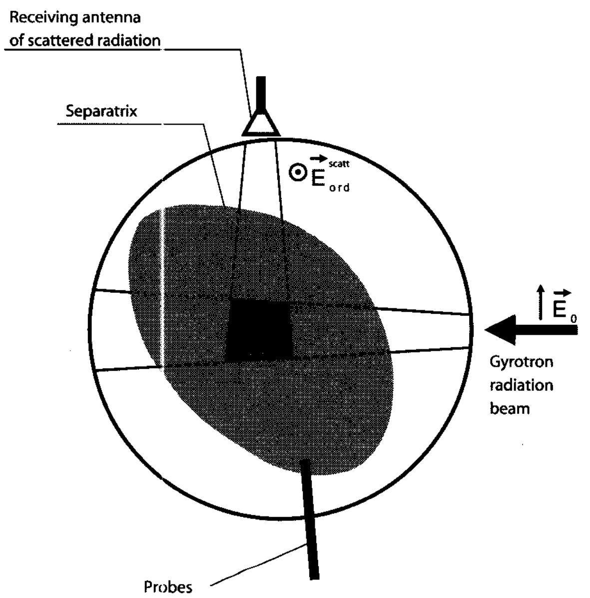

Fig. 1 Scattering geometry for L-2M.

It was shown earlier, that the wavelet-coherence coefficient between fluctuations in the central and edge regions is high [6], which allows us to assume that turbulence in both regions is associated with similar processes. The difference between these processes can be traced in analysis of their probability parameters. Figure 2 shows histograms for the amplitudes of plasma density fluctuations from the central and the edge regions, respectively. The fluctuation amplitude is laid as the abscissa; the number of counts is laid as the ordinate. The shape of the histogram for the plasma edge fluctuations as well as the values of the third and fourth moments allow us to identify the Probability Distribution Function (PDF) of these fluctuations as a Gaussian probability distribution. The histogram for the central region is essentially non-Gaussian. The third and fourth moments are equal to 0.9 and 8.2, respectively. This indicates clearly that the PDF for the plasma center cannot be classed among Gaussian distributions and, consequently, the state of plasma fluctuations in this region is essentially nonequilibrium. The probability of

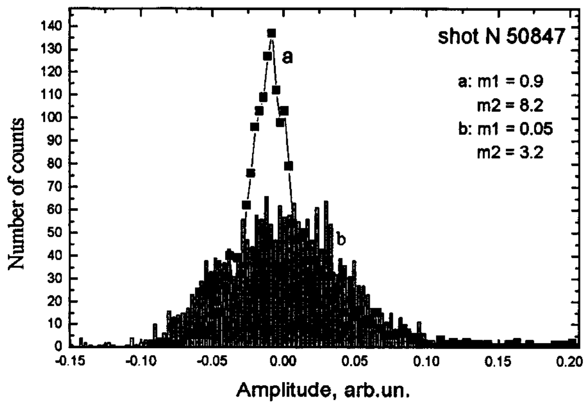

Fig. 2 PDF of turbulent pulsations in (a) the high-temperature and (b) low-temperature regions.

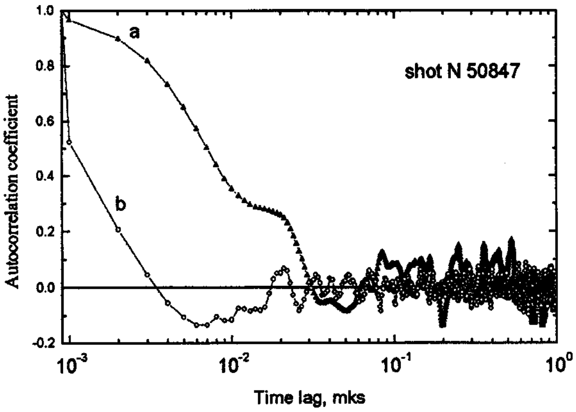

Fig. 3 ACF of (a) fluctuation amplitudes and (b) increments of fluctuation amplitudes in the center of the plasma column.

rare events for density fluctuations increases substantially, which is typical of PDFs with heavy tails. It should be noted that the high-temperature plasma in the central region is under the direct action of the heating microwave beam, whereas the dominant process for the plasma edge is the energy dissipation. It may be suggested that the difference from the Gaussian distribution is a direct consequence of turbulent processes associated with plasma heating in the central region.

The autocorrelation functions (ACF) of the fluctuation amplitudes for the central region and the increments of fluctuation amplitudes are also shown in Fig. 3. The ACF of fluctuation amplitudes has a shape typical for the strong structural turbulence [7]. We can notice that the ACF of increments of fluctuation amplitudes in Fig. 3 is more peaked and contains no pulsations at its tail. This means that the temporal sample of the increments of density fluctuation amplitudes is homogeneous and independent. The correlation time for the increments is much shorter than other characteristic times of the turbulent process under study (the oscillation periods, the amplitude correlation time). This time is about 1–2 μs and is comparable with the characteristic time of turbulent flux measured in the edge plasma [8].

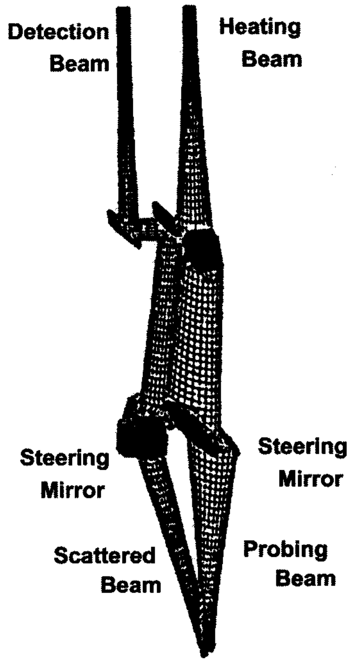

Fig. 4 Scattering geometry for LHD.

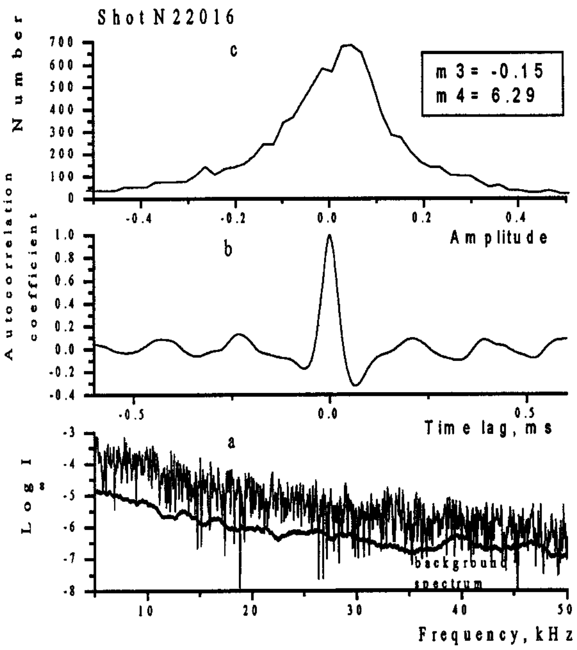

Fig. 5 (a) PDF, (b) ACF and (c) Fourier-spectrum for plasma density fluctuations in core plasma.

3. Scattering Experiment in the LHD

The LHD parameters are described in detail in [9]. The LHD is the largest superconducting helical device with a divertor ($l = 2$, $m = 10$, $R = 3.6$–3.9 m, $r = 0.6$ m, $B < 3$ T). The fluctuations δn in the plasma core were also measured with a homodyne setup. The experimental arrangement is shown in Fig. 4. One of two ECH antennae was adapted for use as a receiving antenna. A 84 GHz gyrotron heating beam launched by the other antenna was used as a probing beam. The scattering volume was situated near the focuses of two launching antennae [10]. For the present geometry of the antenna sets as shown in Fig. 4, the scattering angle corresponded to the fluctuation wave number k = 10–15 cm^{-1}.

Figure 5 shows the PDFs of amplitudes, the ACF, and the Fourier-spectrum of plasma density fluctuations. For the frequency and wave number range observed in this experiment, we can conclude that associated density fluctuations originate from drift-dissipative or trapped-electron instabilities. The shapes of the PDF and ACF exhibit non-Gaussian features of turbulent processes in the central region. This, again, leads us to the conclusion that the heating microwave beam brings on the plasma perturbation processes and the state of plasma fluctuations in this region is essentially nonequilibrium (as it was shown for the L-2M stellarator).

4. Scattering Experiment in the TJ-II Stellarator

The parameters of the TJ-II stellarator are described in detail in [11]. This is a four-period helical axis slellarator, $B_0 < 1.2$ T. The major radius is R = 150 cm, and the mean vacuum separatrix radius is $r_s \leq 22$ cm. The plasma was created and heated with a gyrotron operating at a frequency of f_0 = 53.2 GHz (second harmonic, X-mode). In these experiments, the average plasma density was $n = (0.6 - 0.7) \times 10^{19}$ m^{-3}, the central electron temperature was $T_e(0) \sim 0.5 - 0.7$ keV. Plasma density fluctuations were measured from scattering of a probing microwave beam (wavelength 2 mm, power 0.5 W), as shown in Fig. 6. Note, the 2 mm scattering diagnostic was first implemented in the L-2M stellarator in the early 1990s [12]. In the present experiments, the scattered volume was located at $r = r_s/2$. The measured scattered signals correspond to two wave numbers: 3 cm^{-1} and 6 cm^{-1}.

The spectral, probability, wavelet-coherence and other characteristics were determined for turbulent plasma signals from the region $r = r_s/2$. Below we only present the experimental data referring to a series of TJ-II experiments on the nitrogen cold pulse injection in plasma.

The 2 mm measurements were successfully used to estimate the lag time of the nitrogen appearance in the

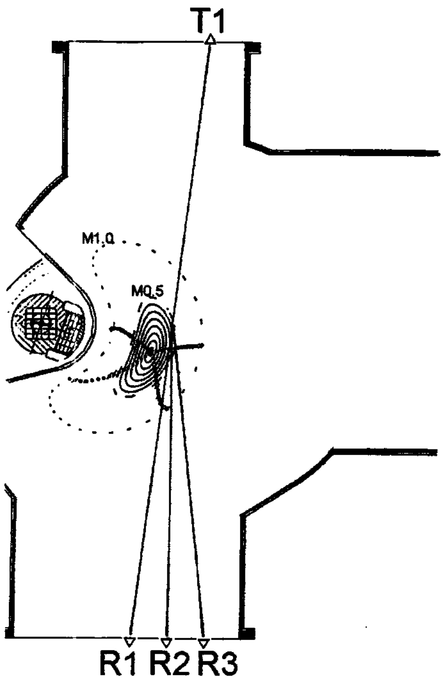

Fig. 6 Scattering geometry for TJ-II.

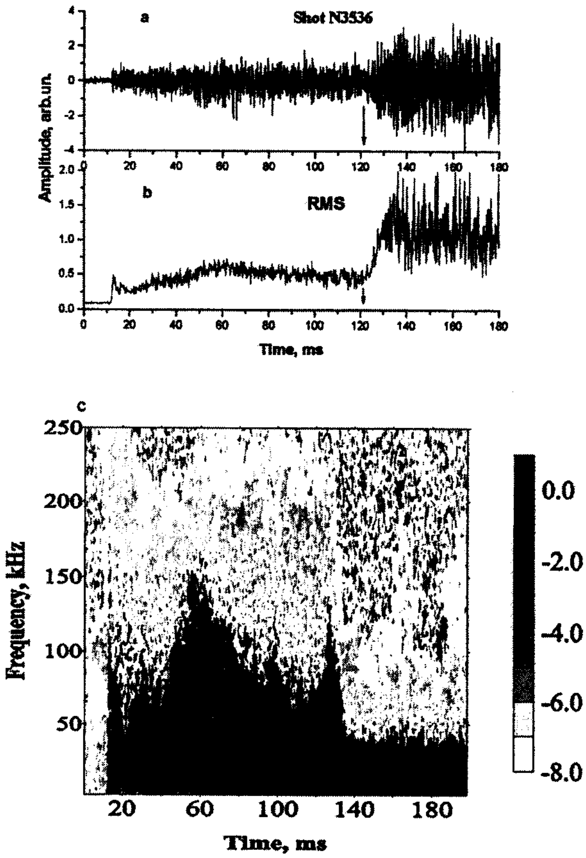

Fig. 7 (a) Scattered signal, (b) RMS deviation of the scattered signal, and (c) Fourier-spectrum of plasma density fluctuations (k = 6 cm^{-1}). The cold nitrogen pulse reaches the scattering region is indicated by arrows. The spectral intensity is shown by gray shadding on the logarithmic scale.

middle radius of the plasma column. Figure 7 illustrates the scattered signal, RMS, and Fourier-spectrum of the turbulent signal with the wave number 6 cm^{-1} for a shot with nitrogen pulse injection. It is seen that the structure of the spectrum changed noticeably when the cold nitrogen pulse reached the scattering region at 135 ms.

5. Conclusion

Comparative measurements of density fluctuations in high-temperature core plasmas were performed in three essentially different devices: L-2M (GPI, Moscow), LHD (NIFS, Toki), TJ-II (CIEMAT, Madrid). The studies of the spectral, correlation, probability characteristics of amplitude of fluctuations in the high-temperature plasma show that the turbulent state of this plasma can be identified as strong structural turbulence. A characteristic feature of turbulence of this kind is that rare events become significant and, hence, should be taken into consideration when constructing a model for turbulent transport in high-temperature plasma. The question of stochastic plasma structures in high-temperature plasma invites further investigation.

This work was supported in part by the Russian Foundation for Basic Research (project no. 00-02-17507 and 01-02-16143) and the LIME program.

References

[1] G.M. Batanov *et al.*, Plasma Phys. Control. Fusion, **40**, 1241 (1998).

[2] V.V. Alikaev *et al.*, Plasma Phys. Reports **26**,1059 (2000).

[3] N.K. Kharchev, K.A. Sarksyan and N.N. Skvortsova, J. Math. Sciences, **106**, 2691, (2001).

[4] G.G. Malinetskii and A.B. Potapov, Modern Problems of Nonlinear Dynamics, URSS, Moscow (2000).

[5] V.V. Abrakov *et al.*, Nucl. Fusion **37**, 233(1997).

[6] G.M. Batanov *et al.*, JETF Lett. **72,** 174 (2001).

[7] N.N. Skvortsova *et al.*, JETP Lett. **70**, 201(1999).

[8] G.M. Batanov *et al.*, JETF Lett. **73,** 126 (2000).

[9] O. Motojima *et al.*, Phys. Plasmas **6**, 1843 (1999).

[10] S. Kubo *et al.*, Ann. Rep. NIFS 1999-2000, 34 (2000).

[11] I. Garsia-Cortes *et al.*, Nucl. Fusion **40**, 1867 (2000).

[12] G.M. Batanov *et al.*, Plasma Phys. Reports **19**, 628 (1993).