# Spatiotemporal evolution of turbulent plasma density fluctuations and of their kurtosis value during modulated ECRH at the L-2M stellarator

G.M. Batanov, V.D. Borzosekov, N.K. Kharchev, A.A. Letunov, V.D. Malakhov,
K.A. Sarksyan, D.G. Vasilkov
*Prokhorov General Physics Institute RAS, Moscow, Russia*

## Introduction

Non-stationary processes at pulsed electron cyclotron resonance heating (ECRH) plasma heating are a convenient instrument for studying changes in both the macro characteristics of a plasma and characteristics of its microturbulence. To study such non-stationary processes on the L-2M stellarator, a mode of ECRH pulse train with a pulse duration of several ms and the same intervals between pulses was used [1]. It was shown that the evolution of energy losses during an ECRH pulse consists of three stages: the low loss stage starting just after the ECRH pulse (stage I), the steep increase of energy losses (stage II), and the quasi-stationary stage (stage III) [2]. It was found that the temporal evolution of turbulent density fluctuations goes in a form of a chaotic sequence of bursts with a duration of 0.1–0.3 ms.

The aim of the present work is to obtain new information on turbulent state of L-2M plasmas with an analysis of the kurtosis value (the fourth standardized moment — M4) of small-scale density fluctuations. Such an approach isn't novel and have been used widely as in earlier work (see review [3] and references therein) as in recent work [4]. The major goal of the kurtosis analysis is to find deviation of probability density function of density fluctuations from the normal distribution that will indicate presence of coherent structures (intermittent events) and anamolous heat tranposrt.

## Experimental set-up

Experiments on the L-2M stellarator were carried out at EC pulse heating durations and intervals between them ~ 2 ms and 4 ms. Only one plasma heating in the experiments was second harmonic (X2) ECRH with a linearly polarized microwave radiation at frequency $f$ = 75 GHz and power $P_{\mathrm{ECRH}}$ of 0.4 MW, which corresponds to power density of 1.6 MW/m$^3$. The average electron density, measured along the central chord of the plasma cross-section, was $n_e$ = 2.0–2.2 × 10$^{13}$ cm$^{-3}$ both during the ECRH pulses and during the intervals between ECRH pulses. The electron temperature measured by electron cyclotron emission at a frequency of 74 GHz in the center of the plasma reached 0.8–1.0 keV and dropped in the intervals between the ECRH pulses to 0.3 keV. A characteristic picture of the evolution of plasma macroparameters is shown in Fig.1.

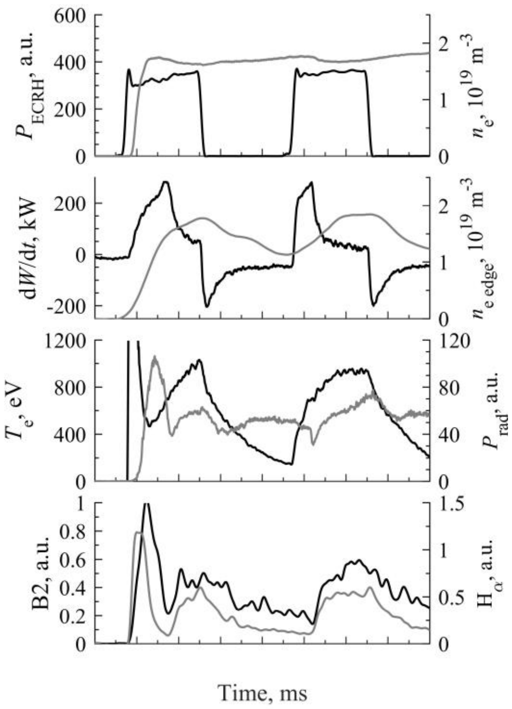


Figure 1. Evolution of plasma macroparameters in the 21371 L-2M discharge (4 ms ECRH pulses, 4 ms pauses). All right axes and axis labels for grey lines and all left for black lines. $P_{\mathrm{ECRH}}$ — ECRH microwave power, $n_e$ — chord averaged electron density, d$W$/d$t$ — plasma diamagnetic response (time derivative of the plasma energy content), $n_{\mathrm{e\ edge}}$ — edge electron density, $T_e$ — central electron temperature, $P_{\mathrm{rad}}$ — radiative losses, B2 — intensity of boron spectral line (B II), Hα — intensity of hydrogen spectral line (Hα).

Diagnostics [5,6] utilized for density fluctuations measurements were: backscattering from short-wavelength fluctuations ($k$ = 30 cm$^{-1}$) — X-wave, measurements averaged over ECRH microwave beam path from the entry point in plasma up to the gyroresonance location; small-angle scattering from long-wavelength fluctuations ($k$ = 1 cm$^{-1}$) — O-wave, measurements averaged over the full plasma diameter; Bragg scattering at $\pi/2$ angles from short-wavelength fluctuations ($k$ = 20 cm$^{-1}$) in the ECRH region — three receiving antennas with two antennas in upper half-plane receiving O-wave and one antenna in lower half-plane of the torus receiving X-wave, local measurements in the vicinity of the plasma center.

**Results and Discussion**

The time series (Fig.2, Fig.3) of density fluctuations intensity ($n_{\sim}^2$) from any used scattering diagnostics represents sequence of intensity bursts above some average level. These bursts are clearly grouped: the first group is observed just after the ECRH pulse start; the second group arises during the stage II of energy losses evolution (rapid increase of energy losses, decrease of electron density in the center of the plasma column); the third group can be seen during the quasi-stationary stage. The most intense group of bursts, as a rule, is the second group.

At pulsed ECRH with intervals between pulses of 2 ms it possible to apply three heating pulses during the typical L-2M discharge. At the time of the third pulse gyroresonance, as well as ECRH absorption region, is located not at the plasma center but is shifted towards inside the torus on 3-4 cm and we have non-axis ECRH in fact. The intensity of density fluctuations in the third pulse is about twice as high as in the second. The silence interval (Fig.3 60.6 – 61.6 ms) between the first group of bursts and the second is longer than for the case of the 4 ms intervals between the pulses (Fig.2), and maximum in the second group is observed at 62.6 ms. Such a slowdown in the evolution of the level of fluctuations correlates with a slowdown in the density drop.

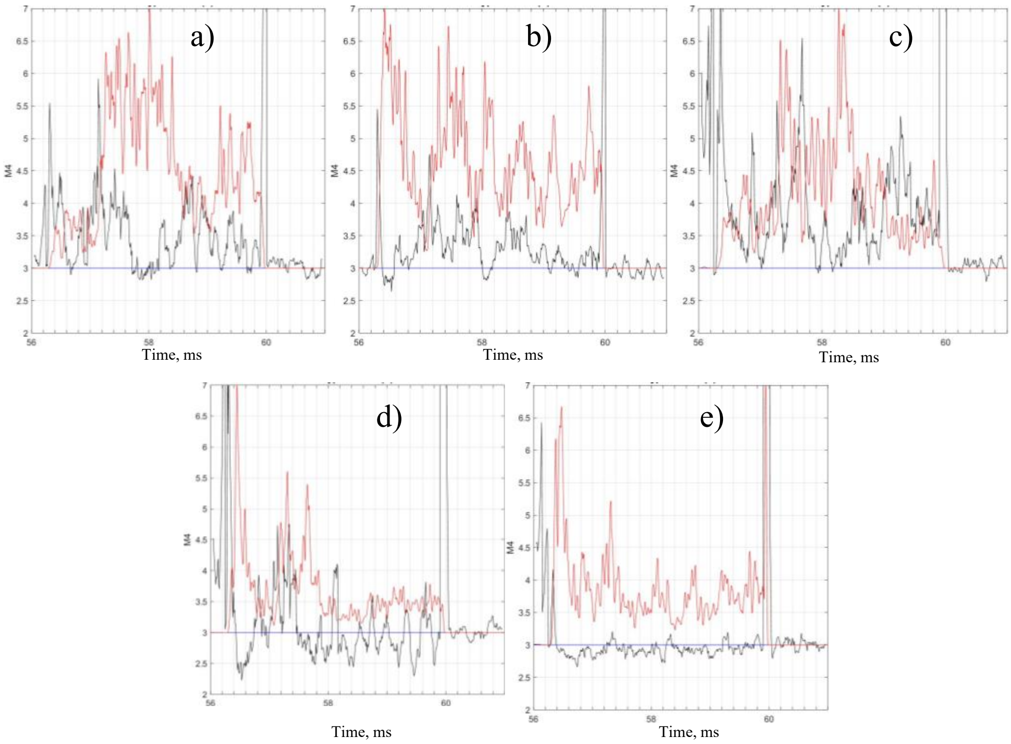


Figure 2. Density fluctuations intensity (red line) in arbitrary units and kurtosis value (black line) during the second ECRH pulse of the 21371 L-2M discharge (4 ms ECRH pulses, 4 ms pauses). a) $k = 20$ cm$^{-1}$, O-wave, plasma center; b) $k = 20$ cm$^{-1}$, O-wave, shifted on 2 cm from the plasma center; c) $k = 20$ cm$^{-1}$, X-wave, plasma center; d) $k = 1$ cm$^{-1}$, O-wave, chord averaged; e) $k = 30$ cm$^{-1}$, X-wave, averaged over the ECRH beam path in plasma.

Strictly speaking, we calculated not the kurtosis (Fig.2, Fig.3) of density fluctuations but the kurtosis of their increments (first order differences). Such an approach is used in statistical analysis to obtain a stochastically independent data set, and it is a standard data analysis technique. As it can be seen from Fig.2 deviation of kurtosis from its value for the normal distribution, i.e. from M4 = 3, has the character of sharp bursts lasting more than 50 μs. Each group of bursts of density fluctuations corresponds to a group of kurtosis bursts (M4> 3.5). The largest deviation from the normal distribution takes place for the second group of density fluctuations. The first group and the second group of M4 bursts precedes or coincides in time with the first and second groups of bursts of fluctuations respectively. The weaker third group of M4 bursts takes place during the wide minimum of the fluctuation intensity and precedes the third group of bursts of the fluctuations. It is noteworthy that results of backscattering diagnostic quite differ from other diagnostics.

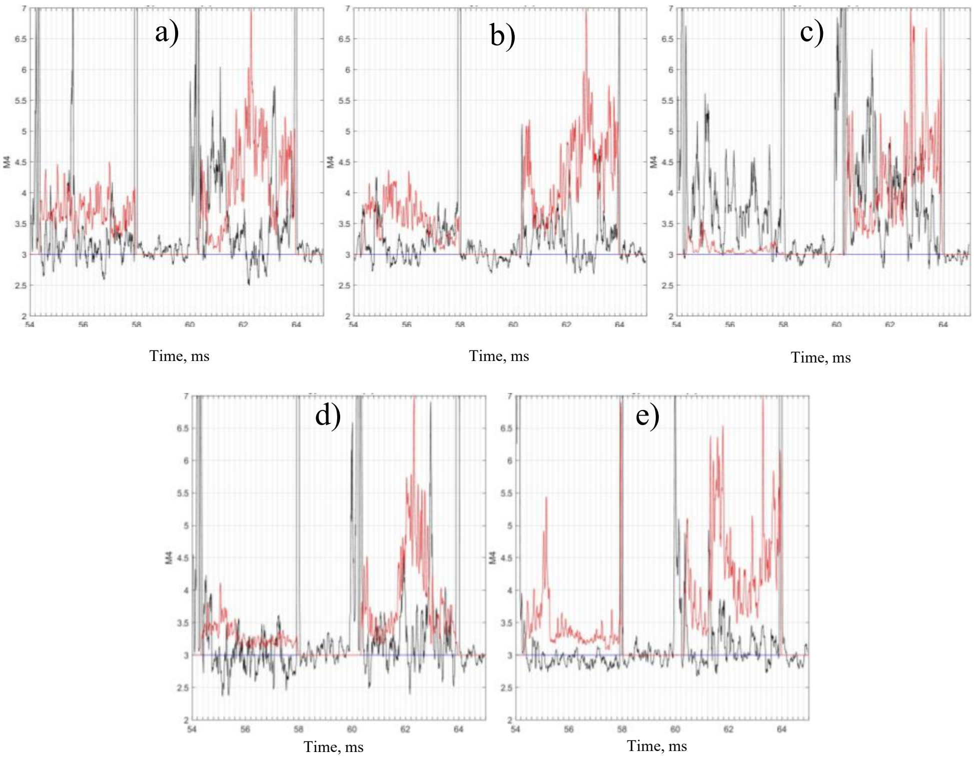


Figure 3. Density fluctuations intensity (red line) in arbitrary units and kurtosis value (black line) during the second and the third ECRH pulse of the 21363 L-2M discharge (4 ms ECRH pulses, 2 ms pauses). a–e) same diagnostics as in Fig.3.

For fluctuations detected by X-wave backscattering, the deviation of M4 from value of 3 is practically absent during the second ECRH pulse. However, in the case of off-axis ECRH during the third heating pulse an intense burst of the kurtosis value also reveals itself simultaneously with a sharp increase of fluctuations intensity. Bursts of kurtosis value above 3.5 suppose an increase in the probability of large amplitudes to occur in the increment of fluctuations at high frequencies. It can be assumed that this observation reflects the occurrence of fluctuations at high frequencies. For example, it was shown in [7] that strong density perturbation caused by the emission of impurities from the vacuum vessel wall led to an increase of density fluctuations intensity in the center of the plasma column at frequencies above 0.3 MHz to appear in the spectra.

The reported study was funded by RFBR according to the project № 18-02-00621.

[1] G.M. Batanov et al. 44th EPS Conference on Plasma Physics, 2017, Belfast, Northern Ireland, P2.154.
[2] G.M. Batanov et al. 45th EPS Conference on Plasma Physics, 2018, Prague, Czech Republic, P4.1099.
[3] T.S. Hahm and P.H. Diamond. Journal of Korean Physical Society 2018, V.73, p. 747.
[4] S. Garland et al. Physics of Plasmas, 2017, V. 24, p. 112307.
[5] G.M. Batanov et al. Plasma Phys. Rep., 2013, V. 39, p. 444.
[6] G.M. Batanov et al., Vopr. At. Nauki Tekh., Ser. Termoyad. Sintez, 2011, No. 2, p. 70.
[7] G.M. Batanov et al. Plasma Phys. Rep., 2017, V. 43, p. 818.