

Wavelet analysis of the parameters of edge plasma fluctuations in the L-2M stellarator

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Abstract. Wavelet analysis results are presented for evolution of the spectral fluctuation characteristics of the edge plasma density and potential in the L-2M stellarator for fast and slow transport transitions. The fast transition comes out as a sharp increase of the energy and electron density within ~0.1ms and the slow one as a weak parameter change during a 0.5 to 1 ms time interval. It is shown that the use of the “Mexican hat” and Morlet wavelets allows one to detect the moment of the fast transition, whereas applying the Haar wavelet adds to this also an estimate of its duration, conforming to the analytical calculations, and reveals the temporal structure of the slow transition.

1. Introduction

Transport transitions (TT) in the L-2M at the stationary discharge stage were first discovered in experiments with the maximum heating power of 250 kW [1]. They appeared as short-time processes being accompanied with a sudden increase of the energy and electron density by 15% (or by 50% with the 500 kW heating power) and a reduction of the plasma potential and density fluctuations at the plasma edge.

This paper presents the wavelet analysis of the plasma edge fluctuations for the fast and slow TTs. The fast TTs are the ones with the duration significantly shorter than the energy confinement time of the plasma. If the transition duration and the energy confinement time are comparable, then such TTs are called slow. Wavelet analysis allows detecting the temporal changes in the process parameters [3] and that is why it is suitable for the time sample research in different plasma diagnostics: dispersion, interferometry, Doppler reflectometry etc. It is shown that the Morlet wavelet and the “Mexican hat” [4] allow to detect the moment of the fast TT, whereas applying the Haar wavelet [4] adds to this also evaluation of its duration in a good accordance with the theory [2] and reflects the slow TT characteristics in more detail than with the two other functions.

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2. Description of the experiment and signal processing

Plasma generation and heating in the L-2M stellarator [1, 2] were realized with the ECR method using the gyrotron complex MIG-3 [5]. In the experiments, the maximum power was 500 kW. In order to study the plasma edge characteristics (at the immersion depth less than 1 cm), the L-2M device employs the movable Langmuir probe system configured to measure the floating potential V_f and the saturation current I_{sat} . Experimental data recording to the processing device occurs at the 100 kHz sampling frequency for the signals with fast TT and 1 MHz for the slow TT. The MATLAB software is used to construct the spectra.

Wavelet analysis is carried out for the V_f and I_{sat} experimental data obtained from the Langmuir probes. The signals are analyzed in the time interval 52 to 60 ms using three basic wavelets: the "Mexican hat" and the Morlet and Haar functions. The first two wavelets have a good spatial and temporal localization, so they are widely applied to the analysis of plasma signals in stellarators and tokamaks [6, 7].

The Haar wavelet is a discontinuous function with a much worse localization than the other ones, so it is used more rarely for the plasma signal analysis, especially for processes with a smooth temporal data evolution. One of the few applications of this wavelet is the analysis of the MHD turbulence in the solar wind [8]. However, as will be shown in Section 3, applying the Haar wavelet can yield more significant results than using the Morlet or "Mexican hat" functions.

In order to isolate the fluctuation components of the signals, the low frequency filtering procedure is performed: at every time moment, the values of the floating potential and the Langmuir probe current averaged over next 25 time points recorded are subtracted from the signals. Then the scalograms are built for the floating potential and the saturation current. For this purpose the signal wavelet transformation is calculated:

$$W_f(a, b) = \frac{1}{|a|^{1/2}} \int_{-\infty}^{+\infty} f(t) \psi\left(\frac{t-b}{a}\right) dt, \quad (1)$$

where $f(t)$ is the signal and $\psi(t)$ is the basic wavelet [4] with the width a and the localization center b . The scalogram is built in the parameter plane (a, b) and the value of $C(a, b) = |W_f(a, b)|^2$ is indicated with gray hue in the scalogram (the lighter the shade, the higher the energy).

The wavelet spectrum [9] reflects the variation of the energy of the signal fluctuations in time, i.e. it is a function not of a and b , but of the frequency ω and time t . The value of this function evolves in time in accordance with the change of the signal characteristics. The correlation between V_f and I_{sat} is also studied in this paper. This characteristic is evaluated using the mutual wavelet spectrum. The mutual, or the cross-spectrum [3, 10, 11] of the signals $f(t)$ and $g(t)$ on a finite time interval T is the function

$$B_{fg}^w(a, \Delta t) = \int_T W_f^*(a, t) W_g(a, t + \Delta t) dt, \quad (2)$$

In the graphs, the spectrum and cross-spectrum values are indicated with the shades of gray.

3. Experimental results

In the L-2 M experiments, the fast TTs were registered in several pulses. The fast transitions bore a great resemblance to the processes observed in [2, 12, 13] including the classic L-H transitions [14]. In the fast TT, the plasma energy and density grow quickly and then saturate (figure 1), and the density parameter remains constant even after turning off the ECR-heating; the H_α radiation intensity decreases and that of B_2 increases [1]. For the signal #16081, the transition is detected approximately at 57 ms and takes about 0.1 ms [2]. In the figures, the fast TTs moments are marked with the dashed line.

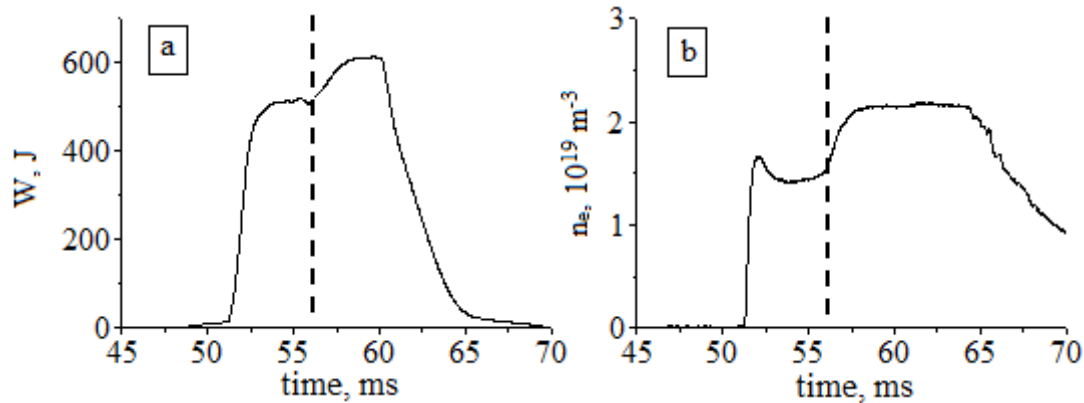


Figure 1. Energy (a) and electron density (b) of the plasma for the signal with the fast TT. Dashed line marks the transition moment.

In the slow TT, one can observe a different kind of evolution of the energy and electron density. One sees from figure 2 that before the transition, the plasma density can either decrease (signal #19124) or increase (signal #19166), but after the TT the density slightly increases. For the discharges #19124 and #19166, the TTs happen at time intervals 56.5 to 57 ms and 55.5 to 56 ms, correspondingly. The start and end moments of the slow TT are marked with the dashed lines.

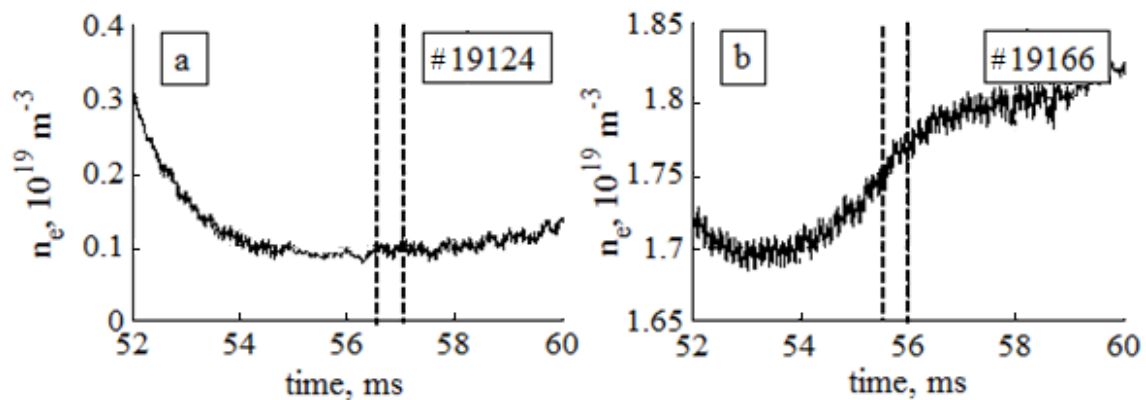


Figure 2. Plasma electron density in discharges #19124 (a) and #19166 (b) with slow TT.

Langmuir probes also detect the change of the signal parameters during the TT. In the case of the fast TT, the V_f and I_{sat} fluctuations decrease by an order of magnitude along with the increase of the plasma density. During and after the slow TT one can observe a slight growth of the amplitude of the potential fluctuations. During the TT the local maxima of the V_f fluctuations are recorded at 56.62 ms, 56.81 ms and 56.91 ms and the minima at 56.70 ms and 56.88 ms. Figure 3 shows the evolution of the floating potential fluctuations for the fast (discharge #16081) and slow (discharge #19124) transitions.

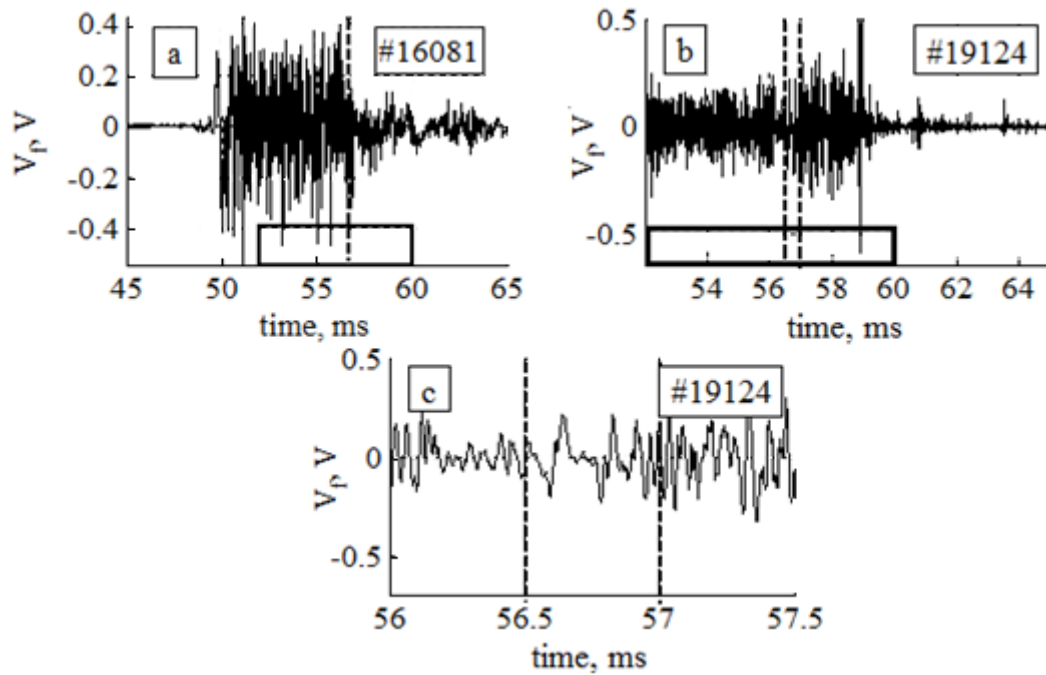


Figure 3. Edge plasma potential fluctuation for the signals #16081 (a), #19124 (b), #19124 in the interval 56 to 57.5 ms (c). The rectangle outlines the time interval analyzed.

Evolution of the plasma edge characteristics after the TT is presented as the wavelet scalograms. For the signal #16081 the scalograms built with the "Mexican hat" and the Morlet wavelet show weakening fluctuations of the floating potential at 57 ms (figure 4) and that of the current at 56.5 ms – approximately at the same time with the change of the plasma energy and electron density. The signal #19124 with a slow TT can also be characterized by the simultaneously changing electron density and floating potential at 56.5 to 57 ms. However, application of the continuous wavelets does not allow estimation of the fast TT duration, nor analyzing the temporal structure of the slow TT in detail.

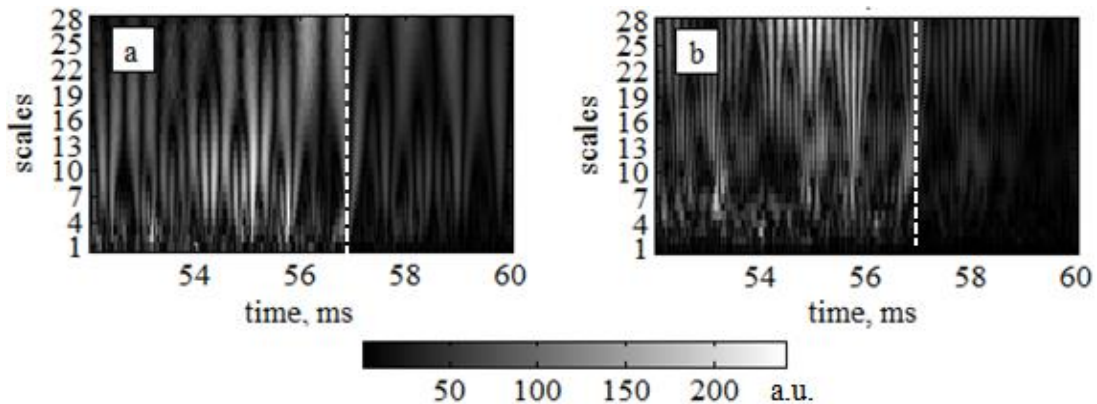


Figure 4. Potential scalograms of the signal #16081, built using the "Mexican hat" (a) and the Morlet function (b).

At the same time, the Haar wavelet (figure 5) allows to solve these problems. The resulting fast TT duration estimate of 0.1 ms shows good accordance with the theory. Scalograms built with the Haar wavelet reflect different behaviour of the potential and current of the signal #16081 after the transition. The potential fluctuations damp instantly at the TT moment and slightly increase at 58 ms, whereas the current fluctuations after the sharp reduction at 56.5 ms decrease gradually for 0.5 ms and then

sustain the average value up to 60 ms. Besides that, the Haar function allows to record all the extrema of the fluctuation amplitude during the slow TT, which is not the case with the continuous wavelets.

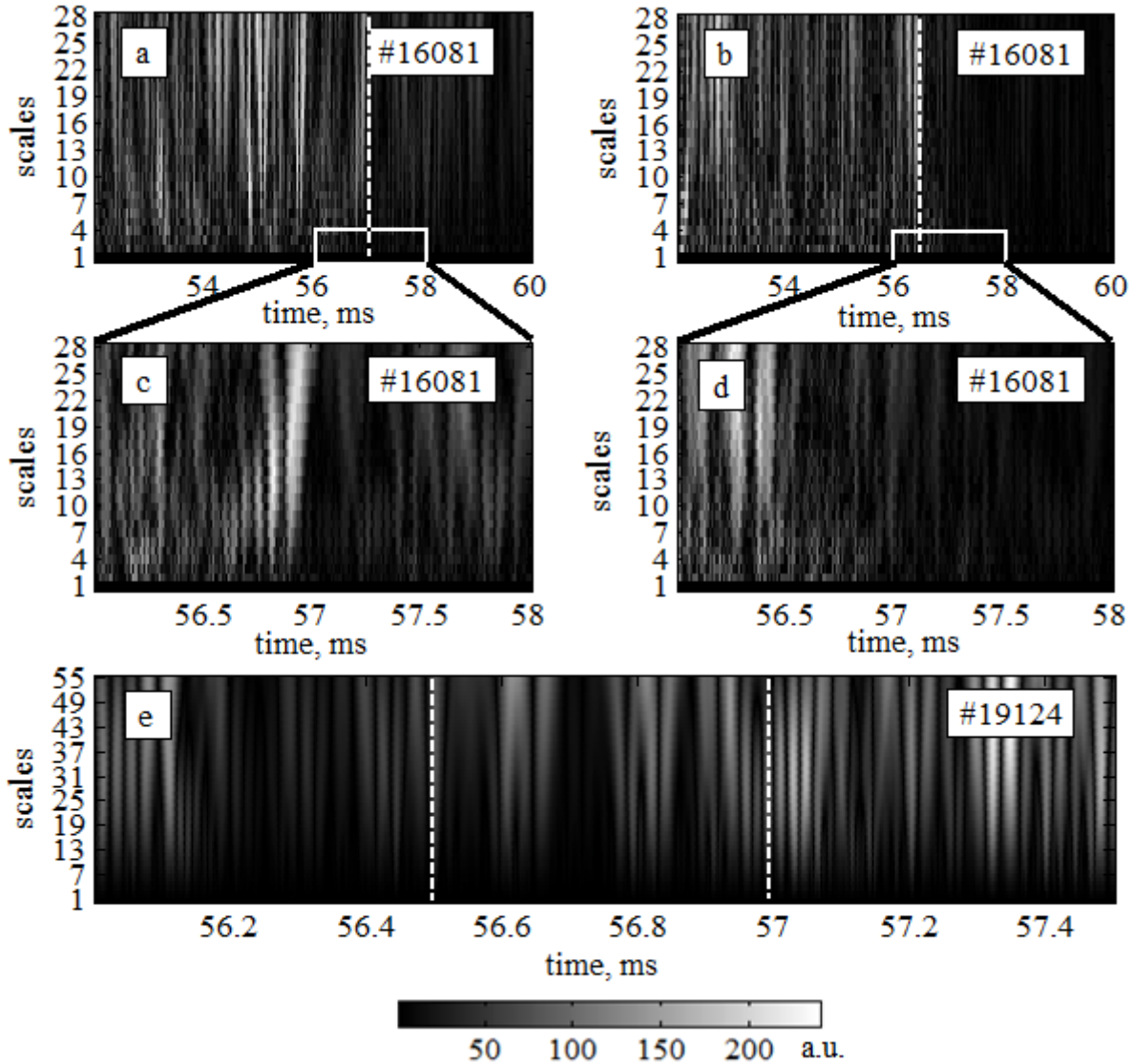


Figure 5. Signal scalograms built using the Haar wavelet: the potential for the signal #16081 (a, c), the current in the discharge #16081 (b, d), the potential in the discharge #19124 (e).

For the signal #16081 the wavelet spectra were also constructed. The analysis proved that before the fast TT, the fluctuations frequencies of V_f and I_{sat} in the range from 0 to 50 kHz are distributed approximately uniformly and after the transition one can see a difference. The energy of the potential fluctuations for the frequencies from 10 to 50kHz decreases sharply and for the lowest-frequency oscillations (less than 10 kHz) it changes insignificantly (figure 6a). The current spectrum for the signal #16081 remains approximately uniform, but its values are greatly reduced (figure 6b).

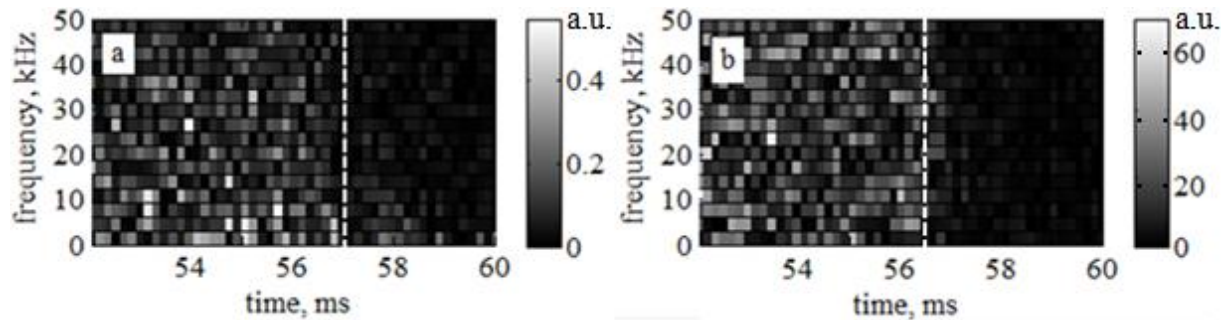


Figure 6. Wavelet-spectrum of potential (a) and current (b) of the signal #16081 with fast TT.

The mutual spectrum of the floating potential and current for the discharge #16081 was also built using the "Mexican hat", Morlet and Haar functions. Coherence maximums are recorded at 52.4 ms and 55.3 ms. The fast TT is accompanied by a sharp decrease of the coherence between V_f and I_{sat} . However, in the case of using the "Mexican hat" and Morlet functions, one can observe blurring of the mutual spectrum. Therefore no clear conclusion about the cross-correlation of the parameters at the TT moment can be made.

The graph constructed using the Haar wavelet (figure 7) shows that at the fast TT moment, the potential, current and their correlation decrease sharply, for much shorter time than the signal #16081 duration. In the time interval 56.4 to 57 ms the spectrum energy is slightly higher than after 57 ms, which is attributed to the time difference of the sharp current weakening and the potential fluctuations (56.5 and 57 ms respectively).

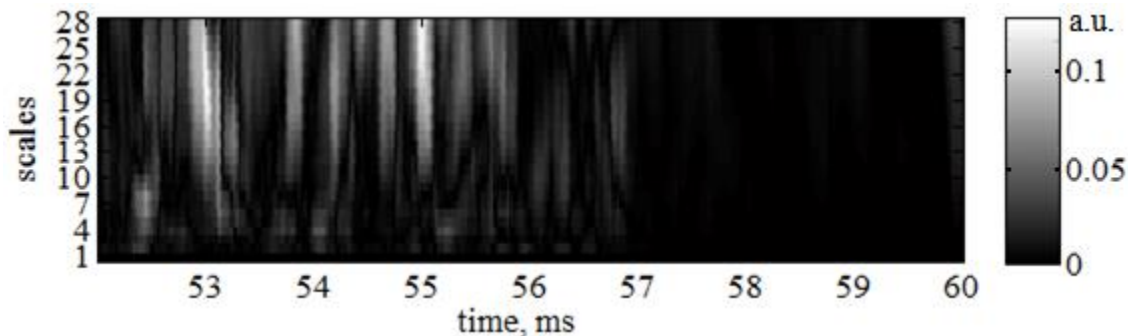


Figure 7. Cross-spectrum of the potential and current of the signal #16081 built with the Haar wavelet.

4. Conclusion

Spontaneous transport transitions are found in the L-2M stellarator experiments with the heating power $P > 250$ kW. The fast TTs are accompanied by a sharp rise in the energy and the plasma density during ~ 0.1 ms and a simultaneous drop of the fluctuations of the density and potential at the plasma edge. In the slow TTs, the plasma characteristics change simultaneously in 0.5 to 1 ms with a slight increase of the potential oscillations after the TT.

Wavelet scalograms reflect the variation of the amplitude of the noise component of the signal. It is the Haar wavelet only that provides also a reliable estimate of the fast transition duration and a detailed analysis of the temporal plasma edge parameters evolution in a slow TT.

The fast transition is accompanied by a sharp fall of cross-correlation of the potential and density parameters in the edge plasma. The smooth reduction of the coherence of the signal #16081 in the time interval 56.4 to 57 ms is caused by the difference of the transition moments for the potential and the current.

Acknowledgements

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References

- [1] Shchepetov S V *et al* 2008 *Plasma Phys. Control. Fusion* **50** 045001
- [2] Kharchev N K *et al* 2011 *Plasma and Fusion Research* **6** 2402142
- [3] Vasilkov D G *et al* 2014 *Proc. of XLI Int. Conf. of Plasma Physics and Controlled Fusion (Zvenigorod)* p 64
- [4] Van Milligen B Ph *et al* 2005 *Phys. Plasmas* **2** 3017
- [5] Daubechies I 2001 *Ten lectures on the wavelets* (Izhevsk, SRP: Regular and chaotic dynamics)
- [6] Batanov G M *et al* 2003 *Plasma Phys. Reports* **29** 363
- [7] Kharchev N K, Skvortsova N N and Sarksyian K A 2001 *J. Math. Sci.* **106** 2691
- [8] Salem C *et al* 2009 *The Astrophysical Journal* **702** 537
- [9] Wickerhauser M V 1991 *Proc. Ondelettes and Pacquettes d'Ondes (Rocquencourt)* p 31
- [10] Torrence C and Compo G 1998 *Bull. Amer. Meteorol. Soc.* **79** 61
- [11] Grinsted A, Moore J C and Jevrejeva S 2004 *Nonlinear Processes in Geophysics* **11** 561
- [12] Letunov A A *et al* 2014 *Proc. of XLI Int. Conf. of Plasma Physics and Controlled Fusion (Zvenigorod)* p 73
- [13] Shchepetov S V, Kholnov Yu V and Vasilkov D G 2010 *JETP Letters* **91** 170
- [14] Wagner F *et al* 1982 *Phys. Rev. Lett.* **49** 1408