Multiparametric Data Processing on Fusion Device Stellarator L-2M

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Abstract. In studying the high-temperature plasma physics, the researcher is faced with the need to process large amounts of semi-structured data. Dozens of multi-channel diagnostics, the results of which are multi-million ensembles of time samples of plasma signals, are usually installed at the same time in thermonuclear devices. These samples contain information necessary to understand the mechanisms of relation between plasma macroparameters (plasma density and temperature, plasma current, magnetic field, auxiliary heating power, etc) and plasma microparameters determined by turbulence (energy, spectral composition, amplitude density distribution, etc). The methods of analysis of plasma signals based on the processing of a single time realization of turbulence cannot be used as a basis for comparison with macroparameters and identification of new patterns of plasma containment in a magnetic trap. The main objective of this work is to obtain information about the relationship between the macro- and microparameters of the plasma based on the structuring of the acquired data and its multi-parameter processing using the modern software and hardware.

1. Introduction
The increasing amounts of information produced by L-2M stellarator make it necessary to automate data processing and systematization of the results. Extensive experience in the processing and analyzing the signals from different plasma diagnostics was accumulated during the existence of the device. The distributed database of the stellarator includes experimental data on more than 10,000 discharges. The main objective of this work was to develop an algorithm for searching and finding new reliable information on the relationship between the macroparameters of the plasma and the microparameters of the turbulence on the L-2M stellarator. The developed algorithm allows one to combine selecting a number of discharges with certain common macroparameters from the database with their processing using the developed software for evaluation of stable (robust) spectral characteristics of fluctuations for further physical interpretation.

The article is devoted to the evaluation of such stable characteristics of the short- and long-wavelength fluctuations of the plasma density in the L-2M stellarator. The considerable amount of experimental data obtained on the fluctuations allows one to compare the turbulence microparameters with the plasma macroparameters necessary for the study of the process of plasma confinement in a toroidal installation.
The aim of this work is to automate data processing on the L-2M stellarator, to obtain robust (stable) Fourier spectra over an ensemble of realizations with the same macroparameters (density, heat capacity, temperature, etc.), to obtain new results by averaging the spectra (selection over calculation parameters), and to build 3D spectra, their projections and multimedia images of their time evolution. The ultimate goal of the work is to develop a hardware-software system of multivariable data analysis on toroidal fusion devices.

2. Experimental Setup
Investigation of the relationship between the macro- and micro parameters of the plasma was carried out the L-2M stellarator. The L-2M device is an \( l = 2 \) stellarator whose parameters are described in detail in [1]. The density of the edge plasma at the radius \( r/a = 0.9 \) (where \( a \) is the separatrix radius) is \( n = 1\ldots2 \times 10^{12} \text{ cm}^{-3} \). The plasma is produced and heated by a 75-GHz gyrotron under the electron cyclotron resonance (ECR) conditions at the second harmonic of the electron gyrofrequency.

Turbulence microparameters were measured [2] by collective scattering diagnostics and Doppler reflectometry [3]. For each diagnostics, Table 1 provides data on its measuring region within the plasma column, the transverse wave components of the fluctuations and the obtained turbulence characteristics.

Table 1. Applied diagnostics, their measuring regions, wave numbers and obtained turbulence characteristics.

| Diagnostics                                      | Wave number, sm\(^{-1}\) | Measuring region, \( r/a \) | Obtained characteristics |
|--------------------------------------------------|--------------------------|-----------------------------|--------------------------|
| Doppler reflectometry                             | 1–2                      | 0,8–0,9                     | 1. Complex Fourier spectra and their projections |
|                                                  |                          |                             | 2. Three-dimensional spectra |
| Collective scattering at the second harmonic of the gyrotron frequency | 24–44                    | 0,3–0,4 0,5–0,6             | 3. Doppler velocity |
|                                                  |                          |                             | 4. Stochastic analysis |
| Small-angle scattering of the gyrotron radiation  | 1–2                      | 0–0,8                       | 1. Three-dimensional Fourier spectra and their projections |
|                                                  |                          |                             | 2. Noise intensity |
|                                                  |                          |                             | 3. Autocorrelation functions |
|                                                  |                          |                             | 4. Stochastic analysis |

The data acquisition system of the L-2M stellarator recording the data from all its diagnostics as well as the device macroparameters and that of its gyrotron complex consists of subsystems of low- and high-speed AD converters of different standards and of distributed data stores. The L-2M database includes tens of thousands of pulses in the different operation modes of the device, which allows one to analyze the microparameters of the turbulence depending on the power of microwave heating in different modes of plasma confinement.

3. Data Processing
The sorted data (time samplings of the fluctuation amplitudes) from the backscattering diagnostics and scattering at the second harmonic of the gyrotron, the small-angle scattering diagnostics, and Doppler reflectometry were used in the multi-parameter complex analysis of the microparameters of the turbulence [4-8].

The sorting was based on the tables of the plasma macroparameters (plasma density, energy content, electron-cyclotron heating power). The sorting and grouping of pulses was carried out in
automatic mode, so as to observe the conditions of the steady-state of the cloud of plasma macroparameters of interest (with possible errors). The sorted data was processed using the previously refined and patented algorithms of spectral analysis of fluctuations [9]. The processing resulted in obtaining spectral characteristics which are stable (robust) over an ensemble of discharges and estimating their errors.

Figure 2 shows averaged fluctuation spectra of the plasma in the stationary phase of three discharges nos. G.38515–G.38517 in sequential time windows 52–54 ms (a), 54–56 ms (b), 56–58ms (c), and 58–60 ms (d). The discharges represent the same regime with microwave heating power of 250 kW and mean plasma density of 1.8–1.9 x 10¹³ cm⁻³. Note that the difference between full widths at half-maximum (FWHMs) and the intensities of the spectra in the appropriate windows was of 10–20%.

Estimates of the spectral components in these spectra were carried out a special method combining both the spectral and probabilistic methods of analysis. Methodology of estimation of the spectral components for the processes of structural plasma turbulence (compound Cox process) was suggested. The method is based on obtaining additional information about the number of turbulent stochastic processes though decomposition of histograms on Gaussian local-scale mixture. The decomposition was performed using the expectation-maximization (EM) algorithm and its modifications such as the stochastic EM algorithm, the median EM algorithm, and the median stochastic expectation-maximization (SEM) algorithm [11]. Figure 2 shows a smoothed robust spectrum with three allocated basic components (bands) which can be used for later comparison with the plasma macroparameters.

Such spectra can be used to determine the average energy of fluctuations over the ensemble of plasma discharges in a device with the same macroparameters and to compare the energy of the spectra in different operation regimes.

Table 2 shows the average values of the energy of long-wavelength fluctuations at different values of the transverse magnetic field for the same input microwave power of EC heating. These values indicate that the level of long-wavelength fluctuations increases with increase of the transverse field while the energy lifetime of the particles and the energy of the plasma column remain the same. The energy lifetime is one of the most important of macroparameters in fusion devices.
(a), 54-56 ms (b), 56-58 ms (c), and 58-60 ms (d). The signals were obtained with the Doppler reflectometry diagnostics.

The signals were obtained with the Doppler reflectometry diagnostics.

spectrum, the dotted lines show the three main spectral components.

### Table 2. Intensity of long-wavelength fluctuations depending on the transverse magnetic field $B_v$

| Confinement mode | Transverse magnetic field $B_v = 0$ Gs, $P=200$ kW | Transverse magnetic field $B_v = -20$ Gs, $P=200$ kW |
|------------------|-----------------------------------------------|-------------------------------------------------|
| Fluctuation energy, arb. units | $5.3 \pm 0.8$ | $7.0 \pm 1.2$ |
| Energy lifetime, ms | $2.6 \pm 0.3$ | $2.6 \pm 0.1$ |
| Number of discharges in the ensemble with the same macro-parameters | 7 discharges | 19 discharges |

### 4. Conclusion

Data on the energy of the plasma fluctuations and the shape of stable spectra was obtained which allowed one to compare two microparameters of the turbulence (its fluctuation energy and energy lifetime) with the plasma confinement time in the L-2M stellarator. Analysis showed that in the L-2M stellarator, the Fourier spectra are robust and the energy of the long-wavelength fluctuations does not correlate with the plasma confinement time when the EC heating power increases [5] while there exists a correlation between the confinement time and the short-wavelength fluctuations [1].

The stable spectra of Doppler reflectometry diagnostic allowed one to determine the parameters required for optimizing the diagnosis and served as the basis for developing a new method for probabilistic analysis [10]. The analysis of the evolution of robust spectra of the diagnostics of the gyrotron radiation scattering revealed the existence of spectral bands in all recorded spatial ranges [4,8].

This work is the first step in the development of algorithms for the comparative analysis of the plasma micro- and macroparameters in toroidal fusion devices. The prototypes of the algorithms were written in MATLAB using the GPU NVIDIA Tesla K20 accelerator. In the future, a transition is planned from prototypes (m-language) toward a complete and functional application as well as obtaining patent certificates for the developed hardware-software complex for data analysis.

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