Spectral and correlation analysis of microturbulences in the spherical Globus-M/M2 tokamaks

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Abstract. Results of the studies on turbulences carried out on the Globus-M2 and Globus-M tokamaks are presented. The main focus was on the analysis of the data obtained using Doppler backscattering method (DBS). The developed codes for the analysis of DBS signals allowed to study the effects of turbulences on the operational mode of the tokamak. A description of the data processing codes is also included. The analysis performed indicates the suppression of turbulence and the formation of a velocity shear during the L-H transition. It was also successfully used to study density fluctuations during and between edge localized modes (ELMs). Spectral and correlation analysis also led to the discovery of limit-cycle oscillations (LCO) and quasi coherent fluctuations (QCFs) during the I-phase.

1. Introduction
Currently one of the most important issues facing the scientific community is the question of realizing efficient ways of generating energy in the future. The most promising at the moment seems to be the use of reactors based on controlled fusion with the use of mainly magnetic confinement systems such as tokamaks and stellarators being proposed. This is not an easy feat, as many problems have to be solved before these devices can be successfully and continuously operated. One topic of particular interest to the plasma physics community is the phenomenon of anomalous transport. It is generally assumed that it is generated by micro-instabilities. The main reason for intense research into this phenomenon is the fact that the transition to H-mode was shown to be caused by their suppression in the plasma [1-4].

Over the years different diagnostic methods have been applied to study the L-H transition. These include beam emission spectroscopy (BES), charge-exchange recombination spectroscopy (CXRS) and gas puff imaging (GPI) [5-7]. One other diagnostic seen as very beneficial to gauge a deeper understanding of the characteristics of the transition to H-mode is Doppler backscattering (DBS) [8]. It had already been implemented on the Globus-M tokamak [9] and has successfully been used to study a variety of phenomena [10-13]. The used system allowed to investigate small-scale density fluctuations with wave-vector values ranging from 2 to 8 cm⁻¹. Now due to the fact that the tokamak was upgraded and now Globus-M2 is in an operational state, it is worth investigating the properties of the H-mode and the L-H transition once more under different conditions. Along with that a new multi-frequency DBS system with 6 more probing frequencies ranging from 50 to 75 GHz was installed which allowed for the investigation of the spatial distribution of plasma flows and small-scale fluctuations. In this...
work we will focus on the methods of analyzing signals recorded by the multi-frequency DBS systems on the Globus-M2 tokamak. There are different ways to study and extract information from these signals and the aim of this paper is to showcase the possibilities of spectral and correlation analysis to investigate turbulences using Doppler backscattering.

This paper is structured as follows. The next segment contains an outline of the possibilities of the codes used to process DBS signals. After that a detailed description of the spectral analysis along with the acquired results is presented. The results of the correlation analysis are also included and come next. The final segment comprises of the conclusion and discussion of the aforementioned research.

2. Program overview

During experiments the signals being detected are analogue signals of 0-2 V. They are processed by the analog-to-digital converter (ADC) with a sampling frequency of 10 MHz. They are then exported in ASCII format and analyzed.

The code consists of several sections the two main ones being dedicated to the spectral and correlation analysis though the program itself isn’t limited to them. For example, the temporal evolution of the DBS amplitude and calculated rotation velocity can also be investigated. While the main focus of the program is to analyze the complex DBS signals, there is segment devoted to the spectral analysis of other real signals such as of magnetic probes, since it is of interest to compare measurements from different diagnostics.

Spectral analysis allows for the process of breaking down any signal into its components at various frequencies which are an important characteristic when it comes to turbulences and varies instabilities. The Fourier transform (fast Fourier transform) provides this connection between the time domain and the frequency domain. The various kinds of spectral analysis of the DBS signals available are presented on figure 1 and the code was written in order to calculate the signal spectrum which describes the distribution of power into frequency components composing it. Since the signals were nonstationary, their spectral analysis was carried out using the windowed Fourier transform method. The code calculates the spectral power in a window of a length that is chosen depending on the problem being solved. The window is then shifted by a time frame and the process continues. It is also possible to smooth these data so as to remove components from the background noise. It is of interest also to have a visual representation of the spectrum as it changes with time. This is why spectrograms were included in the program. They are formed as the dependency of windowed spectral power on frequency and time where the power at each frequency at a given moment in time is transmitted by colour.

![Schematic representation of the performed data analysis.](image1)

![Plasma parameters for discharge #38366. Temporal evolution of a) electron density, b) Dα emission, c) DBS spectral power, d) rotation velocity, e) velocity shear](image2)
The complex DBS signal spectrum is calculated to investigate the Doppler shift of scattered radiation and consequently the plasma rotation velocity. The velocity spectrum reveals some oscillatory phenomena. The modulus of the complex DBS signal showcases the behavior of the fluctuation amplitude. The calculation of the coherence spectrum leads to the examination of the relation between oscillations of various DBS signals.

Correlation analysis of DBS signals can be used for obtaining information on radial correlation properties of turbulence and therefore on the turbulence spectrum with respect to radial wave numbers [14]. However, for us the main goal was the detection of periodic components in the Doppler backscattering radiation, as well as determination of their characteristics. For this purpose, the calculation of cross-correlation functions (CCFs) between velocities measured at different radii or between amplitudes of DBS signals at different radii, and between the amplitude and velocity obtained at the same radius was performed. It was also possible to obtain correlation functions between the DBS signals and other diagnostic signals.

The codes were written in an attempt to be flexible to the constant changes of the experiments and the program’s easy-to-use interface allows to change its parameters in order to adjust to the problem being solved.

3. Spectral analysis results

3.1. L-H transition

The spectral analysis of the DBS measurements allows for the investigation of the L-H transition which is believed to be indicated by a significant increase of plasma density, drop in $D_\alpha$ and development of edge localized modes (ELMs) [15]. These parameters are presented on figure 2a, b for Globus-M2 discharge #38366. The vertical line pinpoints the moment of the transition at around 182 ms. The discharge was also characterized by a magnetic field $B_t$ of 0.7 T, plasma current $I_p$ of 280 kA and averaged electron density $<n_e>$ of $0.2-0.5 \times 10^{20} \text{ m}^{-3}$.

Typical spectra for the complex DBS signal calculated before and after the L-H transition are presented on figure 3. The chosen time stamps are 181.5 ms (before the H-mode) and 185.6 ms (during the H-mode). We can see a clear shift to higher frequencies indicating an increase in the velocity. The rotation velocity increase is showcased on figure 2d. The difference in the evolution of velocities for 20 and 29 GHz probing frequencies indicated the formation of a rotation velocity shear (see figure 2e).

The modulus of the complex DBS signals is proportional to the amplitude of plasma density fluctuations and is used to investigate its evolution. On figure 2c we can see a decrease in it on the periphery for $\rho = 0.91$ with an observable increase of velocity shear. This suppression of turbulences by shear as a possible mechanism behind the L-H transition is at this point an accepted theory.

![Figure 3. Spectrogram of complex DBS signal at $\rho = 0.8$ for discharge #38366. The red line indicates the spectrogram centre of gravity](image)

![Figure 4. Spectral power of complex DBS signal at $\rho = 0.8$ at a) 181.5 ms; b)185.6 ms for discharge #38366](image)
Spectral analysis of the DBS measurements also allows for the investigation of the L-H transition. A spectrogram of the complex signal for the probing frequency of 29 GHz (peripheral plasma at \( \rho = 0.8 \)) is presented on figure 4. The window length was 512 \( \mu s \) with a step of 256 \( \mu s \). It was determined that the rotation velocity can be calculated using the centre of gravity of the spectrograms [16]. A closer look at figure 4 leads to the observation that there is a shift of the centre of gravity immediately after 183 ms which corresponds to the L-H transition. This can also be demonstrated by calculating the spectral power of the signal at different moments in time (see figure 3).

3.2. Edge Localized Modes
Spectral analysis was also applied to investigate the development of Edge Localized Modes during H-mode. They have a significant effect on the loss of particles and energy during discharges in the edge plasma and can cause detrimental damage to the efficiency and physical state of tokamaks. For discharge #38366 the appearance of ELMs is observable on the \( D_n \) signal as periodical bursts starting at 186 ms. We can observe an increase of spectral power at higher frequencies during these modes, while there is a decrease of this power in the inter-ELM periods in the spectrogram on figure 5. The window length was 512 \( \mu s \) with a step of 256 \( \mu s \) in this case.

![Figure 5. Spectrogram of complex DBS signal at \( \rho = 0.7 \) for discharge #38366. The red line indicates the spectrogram centre of gravity](image1)

To investigate further it is worth studying the spectral power during a single ELM (at 191 ms) and between ELMs (190 ms) (see figure 6). One can observe that the spectral power increases for higher frequencies (750-1500 kHz) and decreases for lower frequencies (0-200 kHz) after the appearance of the mode and the frequency band is significantly wider during ELMs. This is consistent with the calculated velocity values that grow simultaneously with the development of ELMs and reduce between them.

3.3. I-phase
While the H-mode is of significant importance, the intermediate phase between L- and H-mode (or the I-phase) has also garnered much attention from the plasma physics community [17]. It was observed that the intensity of plasma density turbulence and \( E \times B \) velocity are modulated with the limit-cycle oscillations (LCO) frequency. This phenomenon is best described by a predator-prey model as it has been observed that the turbulence sustains the \( E \times B \) flow, and growth of the \( E \times B \) flow comes at the expense of the turbulent energy. The DBS diagnostics can be successfully used to study this because it can measure both the \( E \times B \) velocity and the amplitude of plasma density fluctuations.

The #37000 discharge on the Globus-M tokamak was characterized by a magnetic field \( B \), of 0.5 T, plasma current \( I_p \), of 200 kA and averaged electron density \( <n_e> \) of \( 0.3-0.5 \times 10^{20} \text{ m}^{-3} \). The temporal evolution of all plasma parameters for this discharge can be found in work [18]. The indicator of the I-phase was the appearance of the LCO [19]. They are generally observed as low-frequency fluctuations (5-9 kHz) on the \( D_n \) signal. These oscillations were also investigated using the velocity spectrograms for the DBS measurements. The velocity spectrogram and spectral power for the 29 GHz probing frequency calculated with a 4.096 ms window and a step of 2.048 ms are presented on figure 7 and 8.
respectively. Both clearly showcase that the fluctuations detected have a frequency of 9 kHz which is consistent with LCO behavior.

Using spectral analysis, it was also found that another type of oscillations can develop during the I-phase – quasi coherent fluctuations (QCFs) [18, 20-21]. They were observed in the form of broad peaks around the 100 kHz frequency in the backscattered density fluctuations and rotation velocity spectra. The fact that QCFs in DBS amplitude and velocity are of the same nature is reinforced by the spectrograms of these signals’ coherence presented on figure 9. It was calculated for the 39 GHz frequency unfiltered signal with a window of 32 µs and the step 8 µs. It can be seen that during certain times the coherence reaches a value of 0.5. The change in coherence amplitude near the frequency of 100 kHz occurs on a scale of several milliseconds. This suggests that QC-fluctuation appear and disappear with this time scale simultaneously in the power of dissipating fluctuations and the velocity of plasma rotation.

4. Correlation analysis

Correlation analysis proved useful when investigating processes during the I-phase. One example is the investigation of correlation between the calculated velocities of 29 and 39 GHz frequencies on figure 10. The correlation function was calculated with a window of 2048 µs and 1024 µs step. The fluctuations observed correspond to LCO. There is a shift of the correlation which indicates a time delay between the events of the two signals. The value and direction of this shift allows us to calculate the radial velocity of the LCO which is of significant importance when studying the I-phase. While research on the I-phase is yet to be done on the Globus-M2 tokamak, the examples make it clear that these methods can also be successfully implemented to study these kinds of phenomena in the future.
Another example of the analysis is the correlation function on figure 11 between amplitude of plasma density fluctuations and velocity signals for the 29 GHz channel calculated using the same parameters as the one on figure 10. There is a clear periodic relationship between the two signals, indicating the interaction of turbulence and flows at LCO frequencies. This is consistent with the predator-prey model during the development of low-frequency zonal flows in plasma [17].

5. Conclusion

Traditional spectral and correlation analysis methods are used to study density fluctuations and plasma flows in the compact spherical Globus-M and Globus-M2 tokamaks. This is an integral part of signal processing for Doppler backscattering (DBS). For this purpose, codes have been developed that successfully process the information from the multi-channel DBS system on the Globus-M2 tokamak. The programs make it possible to obtain information about the rotation velocity of the plasma, the fluctuation amplitude and the correlation between these values and any parameters measured by other diagnostics.

Examples are presented that show that the developed methods have been successfully used to study the evolution of the velocity profile during L-H transition, the evolution of fluctuation amplitude during the occurrence of ELMs and the phenomena during I-phase. The developed software is intended to be used in further research on the Globus-M2 tokamak.

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