Study of turbulence spectra in a spherical tokamak plasma

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Abstract. A turbulence study was carried out on the Globus-M tokamak. The main method of turbulence studying was Doppler backscattering. Studies have been performed at different radii (in areas with different plasma parameters). It was found that during the transition from H-mode with edge localized modes (ELMs) to the improved confinement mode without ELMs, both turbulent fluctuations of the plasma density and velocity fluctuations are suppressed, which apparently leads to a decrease in anomalous transport.

1. Introduction

As part of the problem of creating new energy sources, work is underway to design reactors based on controlled nuclear fusion. Sources that produce most of the energy at the moment work at the expense of non-renewable natural resources, which, according to forecasts, will run out in 100–200 years with the current level of energy consumption. In addition, these sources are very environmentally unfriendly. As a result, there is an actual problem of creating new energy sources. Reactors based on controlled nuclear fusion have a number of advantages over other energy sources: almost inexhaustible fuel, high environmental friendliness, low damage in the event of an accident.

The main type of reactor based on the controlled nuclear fusion is the tokamak. In these toroidal installations, anomalous transport of energy and plasma particles dominate. Anomalous transport is determined by the turbulence that exists on all tokamaks. In connection with this, intensive studies of turbulent fluctuations in tokamaks are continuing. This report presents the results of studies of turbulence in the spherical tokamak Globus-M. ELMs are one of the types of plasma turbulences [1]; therefore, their study is an actual task.

Studies of turbulence by the Doppler backscattering (DBS) method were carried out on the Globus-M spherical tokamak [2]. Earlier, the DBS method was used to study such plasma objects as filaments [3], the geodesic acoustic mode [4], limiting cycle oscillations [5], and Alfven instabilities [6].

2. Doppler backscattering

The turbulence studies were performed using the Doppler backscattering method. The method of Doppler backscattering is as follows: first, an electromagnetic wave is sent to the plasma at a frequency of the order of tens of GHz. After that, the electromagnetic wave enters the plasma at angles to the boundary magnetic surface, and upon reaching a region with a critical density, is reflected. In the presence of plasma density fluctuations, part of the power is scattered back on these fluctuations and goes back into the radiating antenna, where it is recorded [7, 8]. If density fluctuations move with
velocity $V$, then the frequency of the scattered wave, in accordance with the Doppler effect, differs from the frequency of sounding by $\Delta \omega_D = V \cdot k$, where $k$ is the wave vector of scattering fluctuations. As a result, knowing the scale of the plasma density scattering fluctuations and measuring the frequency $\Delta \omega_D$, one can determine the fluctuation velocity. All velocity oscillations lead to oscillations of the Doppler frequency shift, therefore, knowing the Doppler shift we can do conclusions about the processes that in the plasma.

This diagnostic allows us to determine the value of the velocity of poloidal plasma rotation. The radial velocity of the plasma was not studied in this work. The Doppler backscattering, unfortunately, does not allow to determine the absolute value of the density of fluctuations.

Diagnostics by the Doppler backscattering method makes it possible to measure plasma fluctuation velocities using both ordinary and extraordinary waves depending on the reflectometer setting. In this experiment, studies were conducted using conventional waves.

We assume that we observe a linear backscattering, because during the experiment no non-linear effects were detected in the signals of the reflectometer. Measurements were carried out with a normalized cutoff radius $r/a$ in the range [0.6; 1].

To obtain data not only on the magnitude of the fluctuation rotation velocity, but also on the direction of the rotation, we used the quadrature IQ detection of the backscattered signal. Digitized IQ detector signals were recorded and processed. To determine the time dependence of the Doppler frequency shift, we constructed the spectrogram of the complex signal $I(t) + iQ(t)$ and, thus, determine the dependence of the plasma rotation velocity on time. In the course of the work, spectrograms of the plasma rotation velocity were also constructed. The transition to the H-mode is well seen on these spectrograms, which is characterized by the fact that at the moment of the transition the intensity of the velocity fluctuations decreases significantly, after which it begins to increase again. At the same time, it was possible to obtain spectrograms of the power of the complex signal $I(t) + iQ(t)$, which characterized the intensity of oscillations of turbulent density fluctuations in the range of wave numbers near $k$.

For each shot, measurements were performed using plasma microwave probing at four frequencies simultaneously. Thus, 4 spectrograms of velocities are obtained for one discharge. Since the measurements were carried out at different frequencies, this makes it possible to track the behavior of plasma fluctuations on four different radii (in regions with different plasma parameters).

![Figure 1](image_url). Plasma density (top) and radiation intensity on the Da line (bottom), shot number 36651.
3. The study of the spectrograms obtained in the discharges with the H-ELM-free H transition

Below are the data obtained in the Globus-M tokamak for the discharge number 36651. Figure 1 shows the mean plasma density and the intensity of radiation on the Da line. A plasma was heated by neutral beam injection (NBI). NBI was turned on for 153 ms. A few ms after the NBI was turned on (by 156 ms), a transition to the high confinement mode occurred, accompanied by an increase in the average density and the appearance of peripheral localized modes (ELMs) observed on the signal Da. At 192 ms, a transition to the high confinement mode without ELM (the so-called ELM-free H-mode [1]) occurred, accompanied by the disappearance of the flashes on the Da signal and the corresponding oscillations of the average plasma density.

Figure 2. Spectrogram of the plasma fluctuation velocity, probing frequency 29 GHz.

Figure 3. Spectrogram of the complex signal IQ of the DBS detector, probing frequency 29 GHz.

The H - ELM-free H transition process was investigated by Doppler backscattering. Spectrograms of the plasma fluctuation velocity were constructed. Using the spectrogram shown in Figure 2, you can see the point in time at which the transition from the ELMy H-mode to the ELM-free H-mode occurs. Figure 3 clearly shows the increase in the spectrogram intensity in the [-600; -200] kHz region before the H - ELM-free H transition (180-189 ms). It is characterized by the fact that the intensity of the spectrum of the complex IQ signal decreases, a noticeable failure is formed. The Figure 2 presents a spectrogram of the velocity of plasma density fluctuations at discharge number 36651. The spectra were measured in a 0.5 ms window with a step of 0.5 ms. After the calculations, averaging was performed over a time interval of 1 ms.

Figure 4. Module spectrogram of the plasma fluctuation velocity in the interval [98; 197] kHz, probing frequency 29 GHz.
At the beginning of the experiment (from 156 ms to 185 ms), the cutoff shifts from the inner plasma region to the peripheral one. In the period from 185 ms and up to the breakdown, the density practically does not change, it follows from this that the cutoff does not move and is in the same place. During the transition to the ELM-free H-mode, the density slightly increased, but the intensity strongly decreased. In Figure 3, starting from 192 ms, the spectrum narrows down and the intensity decreases. A decrease in intensity occurs at the same time in which the elms disappear.

To determine the range of velocity spectrogram frequencies at which the transition is observed, graphs of the integral intensity of the spectrogram of the velocity oscillations at these frequencies were plotted versus time.

In Figure 4, at the [98; 197] kHz range, the increase in velocity spectrogram intensity before the transition and a sharp decrease at the time of the mode change are clearly visible.

Figure 5. Module spectrogram of plasma fluctuation velocity in the interval [197; 299] kHz, probing frequency 29 GHz.

In Figure 5, in the [197; 299] kHz range, the dip at the time of the transition is shorter, the intensity increase before the transition is less, the maximum intensity is 2 times less. Upon further consideration of the frequency ranges, with an increase in the lower and upper limits, the dip in the right-hand part of the Figure 5 will increase in time and become smoother, there will be no jump in intensity and the graph will be a relatively smooth increase to 170-175 ms, then decrease to almost zero. to 190 ms and rise to 200 ms.

The graphs in Figure 6 clearly show the moment of transition to the ELM-free H-mode, which is well shown in Figures 4 and 5, and less sharply in Figure 6. Plasma was probed at other frequencies, however, for a more detailed examination, the frequency of 29 GHz was chosen, since it is on it that the effect studied is observed most clearly. Frequency 29 GHz corresponds r/a=0.85. At other probing frequencies, similar spectrograms and graphs are observed, having the same features as indicated in the text above at the same points in time.

4. Conclusion
Plasma diagnostics by the Doppler backscattering method allows to investigate the features of the processes occurring in the plasma. In particular, diagnostics allows one to investigate fluctuations of the plasma rotation velocity in different frequency ranges during the transition of the plasma to different confinement modes.

In the experiment, a drop in the intensity of the spectrogram of the velocity oscillations was observed. This fall is due to a decrease in the intensity of fluctuations in the spectrogram of plasma
fluctuation velocity, which probably leads to decrease in radial turbulent transport and increase in the stability of the plasma. In the high confinement mode without ELMs, the overall intensity of the spectrogram is significantly reduced, the spectrogram shows a decrease of the intensity, which corresponds to a larger frequency range. After 10 ms after the transition to the ELM-free H-mode, the integral intensity of the spectrogram at different frequencies increases sharply, which can be associated with an increase in instability, which leads to a breakdown of the plasma discharge.

The module of the complex signal during the transition in ELM-free H-mode fails too, which indicates a decrease in the intensity of scattering density fluctuations, which can also lead to a drop in turbulent radial transport.

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