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# Determination of filament parameters on the spherical tokamak Globus-M2 using Doppler backscattering

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In high confinement mode (H-mode) in the tokamak Globus-M2, the development of edge-localized modes (ELMs) is accompanied by the appearance of filament structures. Using the Doppler backscattering method allowed to determine the parameters of the filaments during ELMs triggered by and independent from saw-tooth crashes. It was shown that the number of filaments observed during ELMs synchronized with saw-tooth crashes is greater and the area of their observation is wider. The filament velocity during all observed ELM types on Globus-M2 is higher than was the case on the Globus-M tokamak. Filaments that developed immediately before an ELM burst are characterized by smaller amplitudes and velocities. Two diagnostics, Doppler backscattering and poloidal correlation Doppler reflectometry, were used to determine the poloidal velocity of such filaments and the results demonstrated that the velocity values obtained had similar values, which may indicate linear backscattering taking place off these filaments.

**Key words:** high temperature plasma, tokamak, filaments, Doppler backscattering

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Filaments greatly contribute to the transport and loss of particles and energy in both L- and H-modes, can lead to damage of tokamak walls and negatively affect the parameters of the central plasma [1]. They are known to be plasma density perturbations elongated along magnetic field lines that develop in the peripheral region of the tokamak near the last closed flux surface (LCFS), also known as separatrix. On the spherical tokamak Globus-M these structures had been detected and the possibility of using the Doppler backscattering (DBS) method for their study was demonstrated [2]. To correctly interpret the experimental data, simulations of DBS signals using the full-wave code IPF-FD3D were undertaken and the results showed that the experimentally observed quasi-coherent bursts in the signals are a manifestation of backscattering off filaments [3,4]. Based on the fact that the DBS diagnostics works in the case of linear scattering, various parameters of filaments, such as their localization and velocity [5,6], had been determined. Several types of filaments which differed in their characteristics had been found, those during and those between edge-localized modes (ELMs). After the upgrade of the Globus-M tokamak, which involved increasing the basic discharge plasma parameters [7], changes in the characteristics of the observed filaments can be expected. Such a change in behavior is possible due to an increase in the plasma pressure gradient [8,9] which has led to ELMs initiated by saw-tooth crashes [10] now developing along with self-consistent ELMs independent of saw-tooth crashes [11] on Globus-M2. In order to study and determine the parameters of the filaments on the new Globus-M2 tokamak, the DBS diagnostic [12] was employed, which was upgraded to take into account the shortcomings of the old DBS system, and now allows to investigate a larger range of minor radii. This paper is dedicated to the new obtained data about filaments developing under different discharge.

DBS (also known as Doppler reflectometry) is a microwave diagnostic, which involves probing plasma at an angle to the magnetic surfaces, which allows to detect backscattering from the cut-off layer [13]. DBS makes local measurements of the plasma parameters. Using the Doppler frequency shift in the backscattered spectrum, it is possible to determine the perpendicular rotation velocity of the turbulence moving together with the plasma. This velocity component corresponds to rotation in the direction of the diamagnetic or $E \times B$ drift. Also, the amplitude of the complex DBS signal allows to study the behavior of the amplitude of turbulent plasma density fluctuations. This method is used to determine the plasma rotation velocity and radial electric field on various devices. On Globus-M/M2, this diagnosis has also been successfully applied to the study of various oscillating processes such as geodesic acoustic modes (GAMs), limit cycle oscillations (LCO), Alfven eigenmodes (AEs) and others [14].

Globus-M2 has two fixed multi-frequency DBS systems [12] and a system with one changeable frequency. The first multi-frequency system located in the equatorial plane allows to probe plasma at frequencies 20, 29, 39, 48 GHz, the second positioned 14 cm lower at frequencies 50, 55, 60, 65 GHz, and the third located 14 cm higher has one probing frequency that can be changed in the 18–24 GHz

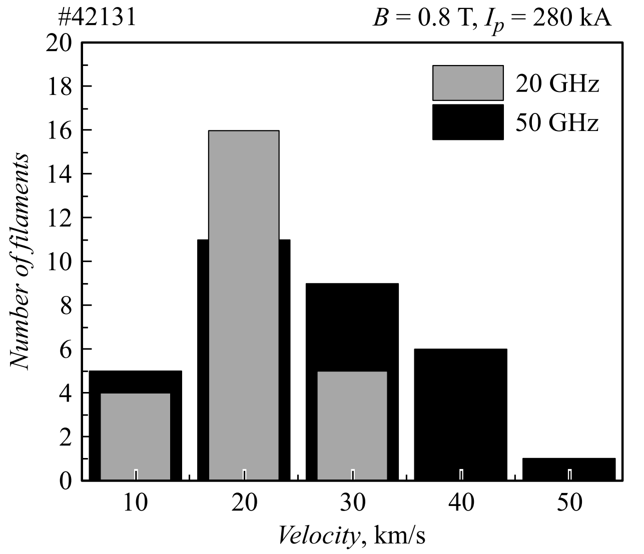


**Figure 1.** Velocity distribution of observed filaments for different DBS frequency channels for discharge #42131.

range. All available probing frequencies have been selected for the purpose of taking measurements in different areas of the tokamak ranging from the inner plasma to the separatrix. The available frequency range corresponds to the normalized minor radii $\rho = 0.5-1.1$ for the discharges discussed in the paper.

On the Globus-M2 tokamak in high confinement mode initiated by neutral beam injection (NBI), filaments were systematically observed during ELMs synchronized with sawtooth crashes. With the help of the updated DBS system, a study of these structures was carried out. The use of high probing frequencies made it possible to investigate the development of filaments in the central plasma region for the first time. On Globus-M2, filament structures have been found in channels with probing frequencies of 20−50 GHz which correspond to normalized minor radii $\rho = 0.7-1.1$. The perpendicular velocities of the filaments were determined in order to compare their characteristics with filaments observed on Globus-M. The results are presented in figure 1 in the form of a histogram, where the black columns correspond to filaments observed in the pedestal region and the grey ones to those observed at the plasma edge. 25 filaments were detected using the 20 GHz probing frequency (radius 60 cm) and 32 filaments using the 50 GHz probing frequency (radius 55 cm) in the discharge #42131. Each of the filaments found was observed on only one channel, indicating that the radial size of the filaments does not exceed the distance between the cut-offs (about 1.5 cm). It is important to note that peripheral filaments had poloidal velocities of 10−30 km/s, while filament structures in the pedestal region had velocities up to 50 km/s. The absence of filaments with such high poloidal velocities on the 20 GHz channel explains why the channel had fewer filament structures. Filaments with a large poloidal velocity component appear to have a very small radial component and thus may not reach the separatrix during the time of their existence. Similar filament behavior was observed on the MAST tokamak [15] where filaments with large poloidal velocity components had a very small radial component and, on the contrary, filaments with a large radial velocity would slowly move in the poloidal direction. Additionally, it is worthy of note that the measured velocities were higher than those on Globus-M [5].

After the increase of the magnetic field and plasma current on the tokamak Globus-M2 self-consistent ELMs often appeared. This phenomenon is associated with an increase in the plasma pressure gradient and peripheral current density, which has led to the destabilization of peeling-ballooning mode. With the help of the DBS diagnostic it was confirmed that filament structures also develop during such ELMs. An example of the observed filaments is given in figure 2 where the spectrogram of the complex DBS signal for the 29 GHz frequency is presented. There is a $D_\alpha$ line introduced to illustrate that the development of the filament structures occurs during an ELM burst. In this case, two filaments with the same poloidal velocity of 15 km/s (or the Doppler frequency shift of 800 kHz) were found, which can be seen in the form of bright spots on the spectrogram. It is important to note that during a single burst of a self-consistent ELM usually one or two filaments are observed, while during ELMs triggered by saw-tooth crashes up to 5 filament structures can develop. This can be explained by the fact that the bursts of the self-identified ELMs are significantly shorter in time (0.1 ms). In addition, filaments during self-consistent ELMs are characterized by peripheral localization and are

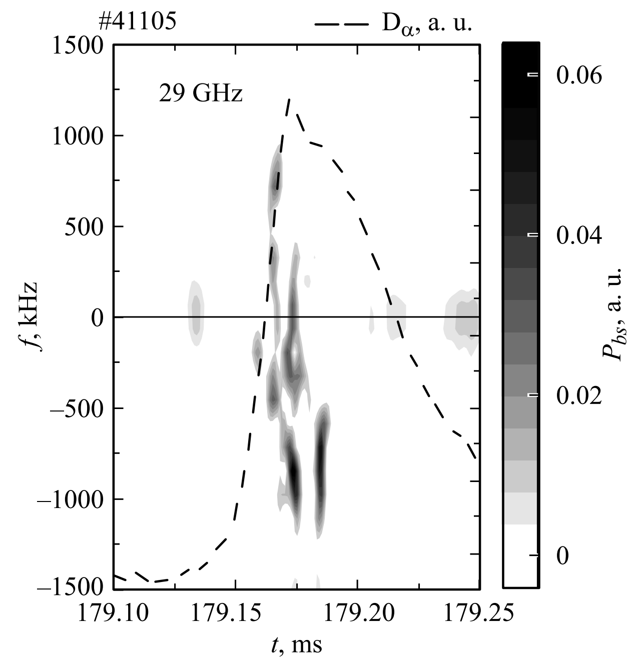


**Figure 2.** Spectrogram of complex DBS signal for probing frequency of 29 GHz for discharge #41105. The bright spots are filaments. The dotted is the $D_\alpha$ signal during an ELM burst.

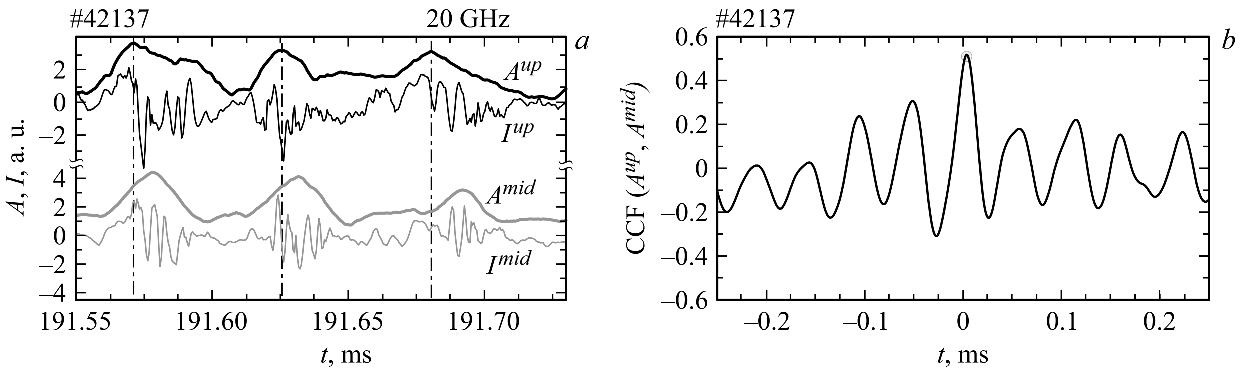


**Figure 3.** *a*) Temporal evolution of DBS signals and their amplitude for the probing frequency 20 GHz. Black is the signal of the DBS system located 14 cm above the equatorial plane and grey is for the DBS system located in the equatorial plane; *b*) the cross correlation function for the amplitudes of the signals with 20 GHz frequencies for the two DBS systems.

observed primarily on the 20 GHz and 29 GHz channels of the DBS system. This may be due to the fact that the saw-tooth crashes, which occur in the central areas of the plasma and therefore disturb the plasma current not only at the periphery, destabilize the peeling-ballooning instability in a larger radius range, thereby initiating associated ELMs with wide localization.

Groups of filaments have been observed not only during the ELM burst itself, but also right before the ELM, when the peeling-ballooning instability appears to be approaching its development threshold. Such filaments were characterized by lower amplitude and slightly lower poloidal velocities. Since filaments are known to be structures stretched out along magnetic surfaces lines, poloidal correlation Doppler reflectometry was implemented on Globus-M2 to determine the direction of the poloidal movement of filamentous structures and as an alternative way to assess of the velocity of this movement. For this purpose, two DBS systems were used: the ones located in the equatorial plane and 14 cm above. The application of poloidal correlation reflectometry involves the analysis of data collected at the same radius, so the same 20 GHz frequency was used on the two systems in the experiments. An example of the obtained signals is given in figure 3, *a* where the DBS signals and their amplitudes are depicted. You can see that the filaments were observed on both channels, but with a time delay: first the burst occurs on the top system and then on the bottom, as demonstrated by the black vertical lines. This indicates that the filaments are moving in a top-down direction. Correlation analysis was applied to analyze this delay. Figure 3, *b* depicts the cross correlation function (CCF) calculated for the signal amplitudes for the probing frequency of 20 GHz for two DBS systems (systems #1 and #3) in the presented discharge. The cut-offs are located on the same radius ($r = 60$ cm) but are spaced 3.5 cm in the poloidal direction. The maximum value of the CCF of 0.52 corresponds to the 4 $\mu$s time delay. The obtained values of the distance between the cut-offs and the time delay can be used to estimate the poloidal velocity of the filament movement, which for the discharge in figure 3 was about 8 km/s. In this case, the velocity determined by the Doppler shift turned out to be very close to this value and was about 7 km/s. The coincidence of the velocities measured by the two different methods indicates that scattering off the filaments occurred in a linear mode. This is to be expected for scattering off filaments before ELMs, as their amplitude is small. However, if the amplitude of the filaments is greatly increased, the velocity recovered by the Doppler frequency shift may differ from the real value, as indicated by simulations performed using the full-wave code IPF-FD3D [4]. Thus, the application of simultaneous spectral and correlation analysis of DBS signals to determine the velocity of filaments demonstrated in this work was found to be effective for investigating parameters of filament structures.


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### Conflict of interest

Authors declare no conflict of interest.

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