Observations of filaments at the TUMAN-3M tokamak

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Abstract. Some factors limiting an increase in the plasma pressure at the periphery of the tokamak plasmas can arise when the improved confinement is achieved in the H-mode. It happens when the edge localized modes (ELMs) develop in tokamak plasmas, and the factors mentioned above manifested themselves in the form of quasi-periodic filamentary structures, or filaments. The formation of such structures results in the occurrence of the anomalous energy and particle flows onto the first wall and divertor plates of tokamaks. Studies of the filaments were previously performed at tokamaks with divertor configuration using various plasma diagnostic methods, including the Doppler backscattering method. The paper presents the first observations of the filaments at the TUMAN-3M, which is the tokamak with limiter configuration. The filaments were studied using the Doppler backscattering method. Plasma was probed by the double-frequency microwave radiation of the O-wave in the frequency range of 27–37 GHz. The data were obtained in the H-mode regime initiated by the pulsed gas injection, in which the ELM-like events are observed. The poloidal velocity of the filaments and their radial localization were determined, and the radial and poloidal sizes of the filaments were also estimated.

1. Introduction
In the region of formation of the peripheral transport barriers in tokamaks, structures often appear that are extended along the magnetic field lines and localized in the transverse direction. These structures (the so-called "filaments") can considerably contribute to the transport of particles and energy in the peripheral region and determine the flows onto the walls of the tokamak chamber and divertor. In this regard, the filaments were actively studied in tokamaks with divertor configuration using various diagnostic methods: the fast video shooting, the electrical and magnetic probing, and the Thomson scattering [1–4].

The paper presents the first results of filament observations at the TUMAN-3M limiter tokamak, which were performed using the Doppler backscattering method.

2. Doppler backscattering method for filament investigations
The Doppler backscattering (DBS) diagnostics is based on recording the backscattered microwave radiation which appears after the microwave beam with oblique incidence falls onto plasma. The direction of microwave beam coincides with the diamagnetic drift direction near the cutoff plasma region. Microwaves are scattered on the plasma fluctuations with the selected wave vector \( \mathbf{k}_\perp \). The wave vector \( \mathbf{k}_\perp \) should satisfy the Bragg condition for backscattering \( k_\perp = 2k_i \), where \( k_i \) is the wave vector of the incident wave in the cutoff region. When the density fluctuations that scatter...
microwaves move in the diamagnetic drift direction with a velocity of $V_\perp$, the Doppler frequency shift of the backscattered radiation appears $\Delta \omega_D = k_\perp \cdot V_\perp$.

![Figure 1](image)

**Figure 1.** Results of modeling the DBS response to the filament movement. (a) the calculated real parts of weighting functions for two probing frequencies of 37 GHz and 35 GHz. The trajectory of the filament is shown by dotted line; and (b) the calculated responses of the DBS detectors operating at frequencies 37 GHz (top) and 35 GHz (bottom).

If the filamentary perturbations of plasma density occur in the vicinity of the cutoff region, then the quasi-coherent oscillations will be observed on the DBS signals. The frequency of these oscillations and their duration will be determined by the velocity of the filaments and the time of their passage through the scattering volume, respectively. Similar observations were performed at the Globus-M tokamak [5] and later at the ASDEX-Upgrade tokamak [6, 7].

In order to explain the process of radiation backscattering on the filamentary structures in plasma of the TUMAN-3M tokamak, it is convenient to use the in-phase (I) and quadrature (Q) representations of the DBS detector signals obtained in the Born approximation [8, 9]:

$$ I(t) + iQ(t) = \eta \int \delta n(r, t)[W_I(r) + iW_Q(r)]d^3r $$

Here, $W_I$ and $W_Q$ are the real and imaginary parts of the 2D weighting function, $\delta n(r, t)$ are the scattering fluctuations of the plasma density, $\eta$ is the dimensional coefficient of proportionality [9]. As an example, two real parts of the weighting functions, calculated for two probing frequencies, are presented in Fig. 1a. The calculations were performed for the density profile measured in the TUMAN-3M tokamak. The spatial periodic structure of the alternating weighting functions is clearly visible, which determines the selection of scattering fluctuations in the k-space.

If the filament with the transverse size close to the spatial period of the weighting function moves across the scattering volume in the poloidal direction, as shown in Fig. 1a for a frequency of 37 GHz (near $r = 17$ cm), then, in accordance with relation (1), the signals of the IQ detector begin to oscillate, forming a bunch of quasi-coherent fluctuations (BQF). The corresponding IQ detector signals are shown in Fig. 1b (top). The signal oscillation frequency is determined by the filament velocity. The sign of the phase shift between the $I(t)$ and $Q(t)$ signals is determined by the sign of the Doppler frequency shift $\Delta \omega_D$ and corresponds to the direction of the filament movement (in Fig. 1, the filament moves from bottom to top). If the filament does not cross the scattering volume, as shown in Fig. 1a for a frequency of 35 GHz (near $r = 18.5$ cm), the BQF amplitude decreases to almost zero.
Figure 2. Time evolution of plasma parameters in the TUMAN-3M shot #17013113. (a) the central-chord-averaged plasma density; (b) the intensity of the D\textsubscript{\alpha} line; (c) gas puffing; (d) the magnetic probe signal; and (e) SXR radiation. The time of transition to the H-mode is shown by the vertical line.

Figure 3. (a) the D\textsubscript{\alpha} radiation intensity; (b) and (c) the I and Q signals of the DBS detectors, respectively (the probing frequency is 37 GHz). The time intervals of observation of filaments are painted in blue.

3. Experimental results

3.1. Experimental setup
The formation of filaments was studied in the TUMAN-3M tokamak shots with a transition to the ohmic H-mode triggered by the gas puffing pulses [10]. The characteristic feature of the ohmic L–H transition is an increase in the plasma density accompanied by a sharp drop of the D\textsubscript{\alpha} emission intensity. The transition occurring at the 57\textsuperscript{th} ms is clearly seen in Figs. 2a and 2b.

The periodic flashes on the D\textsubscript{\alpha} signal were observed after the transition to the H-mode (Fig. 2b), which occur synchronously with the sawtooth oscillations (Fig. 2e). The sawtooth oscillations are associated with the appearance of the q=1 magnetic surface in the plasma and are clearly visible on the SXR and average density signals measured along the central and other chords. After the internal reconnections, the heat and plasma flows from the axial region increase the plasma density and temperature at the periphery. The resulting increase in the pressure gradient can lead to the development of the MHD instability, which ultimately leads to ELM-like flashes on the D\textsubscript{\alpha} signals.
To study density fluctuations during ELM-events, the double-frequency Doppler reflectometer operating in the frequency range of 27–37 GHz was used. For this frequency range, the cutoff region at a density of $2 \times 10^{19} \text{ m}^{-3}$ was located near the region of the transport barrier formation.

3.2. Filaments time evolution

The groups of quasi-coherent oscillations were detected on the Doppler backscattering signals. These oscillation groups were observed (blue color in Fig. 3b) synchronously with the flashes on the $D_\alpha$ signal (Fig. 3a). At the same time, between the groups, the DBS signal becomes turbulent without isolated bunches of oscillations, and its spectrum broadens. If the quasi-coherent oscillations can be considered as filaments (in accordance with the model described in section 2), then an ELM-event in the TUMAN-3M is a set of filaments that move one after another in the poloidal direction in equal time intervals.

3.3. Distinctive features of filaments

Figures 4a-4d presents the signals of two DBS frequency channels during one of the ELM-events. The bunches of quasi-coherent oscillations are observed only in the high-frequency channel (at a radius of about 17 cm). At a radius of 18.5 cm, the filaments are not observed, which indicates the radial localization of these structures.

In Fig. 4e, the spectrogram of the DBS signal for a frequency of 37 GHz ($r = 17\text{ cm}$) is shown. The filaments manifest themselves on the spectrogram as the bursts with duration of about 6 $\mu$s and a frequency of about 550 kHz. This frequency corresponds to a poloidal rotational velocity of about
11 km/s. The bunches appear with a characteristic period of approximately 12 μs. Thus, during one ELM-event, ten filaments (m = 10) rotating one after another can be observed simultaneously in one poloidal section.

The scattering of microwave radiation on filaments occurs most efficiently, when their poloidal size is of the order of 2π/k⊥, which is of the order of 1 cm under the experimental conditions at the TUMAN-3M tokamak. The radial size of the filament cannot be determined with the help of only two radial DBS points. However, in some cases, the filaments were observed simultaneously in two DBS frequency channels. The radial size of these filaments cannot be less than the distance between the cutoff regions for the frequency channels ρ = 1.5 cm.

4. Conclusions

The use of the Doppler backscattering diagnostics at the TUMAN-3M tokamak made it possible to discover the filamentary structures in the vicinity of the region of the transport barrier formation.

The filaments manifest themselves as a train of the quasi-coherent oscillations successively appearing on the Doppler backscattering signals. The filaments occur in groups, and their occurrence is correlated with the flashes on the Dα signal. The ELM-events initiated by the sawtooth oscillations are assumed to be the probable reason for occurrence of these bursts. The filament groups appearing during the ELM-events were observed in many experiments at tokamaks with divertor configuration of the magnetic field (see, for example, [1]).

The characteristic filament velocity in the poloidal direction is 10–12 km/s. It was ascertained that the filaments develop in the vicinity of the minor radius r = 17 cm and do not occur outside the radius of r = 18.5 cm. The poloidal mode number of the filaments is m = 10.

At the TUMAN-3M and the Globus-M tokamaks, the temporal evolutions of the filaments are similar [5]. However, at the TUMAN-3M tokamak, the filaments are localized deeper in the plasma at radii, which are considerably less than the radius of the last closed magnetic surface.

Acknowledgments

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