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Observation of plasma density oscillations using the microwave interferometer of the T-15MD tokamak

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The capabilities of the microwave interferometer of the T-15MD tokamak for observing and analyzing plasma density fluctuation parameters are presented. The results of the first experiments on measuring line-integrated plasma density oscillations at the T-15MD tokamak are reported. Using the microwave interferometer, low-frequency magnetohydrodynamic (MHD) perturbations, including sawtooth oscillations, were detected. It is shown that the amplitude of the microwave interferometer signal can provide additional information about plasma perturbations.

Keywords: tokamak, amplitude effects, sawtooth oscillations, low-frequency modes

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Introduction

One of the key problems of high-temperature plasma physics is study of processes of transfer of particles and energy. It is demonstrated by experimental studies that in toroidal units, such as the stellarator and the tokamak,transfer coefficients significantly exceed predictions of a neoclassical plasma theory [1]. It is deemed that this anomalous transfer is caused by development of small-scale instabilities in plasma, turbulences. Performing experiments of measuring plasma oscillations and determining their characteristics will make it possible to extend an experimental database and to deepen understanding of the turbulent transfer mechanisms in the future. One of the main methods of analysis of turbulence is to measure electron density oscillations in tokamaks by means of various diagnostics [2–4]. One of these diagnostics is interferometry.

Interferometry methods are actively applied for measuring an electron density of a plasma. When passing through the plasma, the electromagnetic wave gets an additional phase incursion that under probing at a usual wave and when $\omega \gg \omega_p$ (where ω is a frequency of the electromagnetic wave, ω_p is a plasma frequency) can be assumed to be proportional to a linear electron density of the plasma [5]:

$$\Delta\varphi = -r_e\lambda \int\limits_L n_e(l)dl, \tag{1}$$

where r_e is a classical electron radius, λ is a length of the electromagnetic wave, a density integral along a probing chord will be hereinafter designated as nl. Thus, output data from the interferometric diagnostics are integral values of nl (or the linear density) [5].

The main problems of tokamak plasma interferometry include:

1) measuring and controlling an average value of the electron density $\langle n\rangle$;

2) restoring a radial distribution $n(r)$ across a cross section of a plasma cord.

Nevertheless, often, application of interferometers in a millimeter- and submillimeter-band, which are highly sensitive to the plasma density and high time resolution of the measurements performed, makes it possible to observe small ($\delta nl/nl \sim 0.1\,\%{-}1\,\%$) oscillations of the plasma chord density nl. Such measurements were also analyzed in other tokamaks. The following was detected:

1) low-frequency MHD oscillations ($f \sim 1{-}10$ kHz) [6–10], including sawtooth oscillations and tearing modes [9] as well as an internal kink mode [10];

2) high-frequency oscillations within the range $f \sim 100{-}200$ kHz [11,12] with detecting Alfvén cascades [4].

It is obvious from the previous studies [4,10] that when measuring density oscillations it is expedient to consider not only a restored phase (linear density) signal, but an amplitude of an interferometer-recorded signal, since the processes in the plasma, for example, deviation of a ray due to refraction [13] and rotation of a polarization plane due to the Faraday effect [14], results in variation of power arriving to a probing radiation detector, thereby making it possible to observe local changes of n.

The present study is dedicated to application of the VHF-interferometer as a tool for observing oscillations of the plasma electron density. The present study provides an estimate of operating limits of the VHF-interferometer for observing oscillations as well as results of measurements of the parameters of electron density oscillations, which are done using the VHF-interferometer in the T-15MD tokamak.

1. Experimental unit and equipment used

The T-15MD [15] tokamak is output to design parameters in NRS „Kurchatov Institute“: the large radius $R = 1.48\,\mathrm{m}$, the small radius $a = 0.67\,\mathrm{m}$, the plasma current I_p is up to 2 MA, the toroidal field at the axis B_T is up to 2 T, the plasma density $\langle n \rangle$ is up to $10^{20}\,\mathrm{m}^{-3}$. The unit is intermediate between spherical and classical tokamaks (the aspect ratio $A = 2.2$) and is designed for operation in a divertor configuration of the plasma cord with elongation $k_{95} = 1.7-1.9$ and triangularity $\delta_{95} = 0.3-0.4$. Up to now, there have been plasma shots produced with duration of up to 2 s, the plasma current of up to 620 kA and sustaining the divertor configuration of duration of the 1 s-scale.

The electron density of the plasma of the T-15MD tokamak is measuring using the VHF-interferometer [16] with the wavelength of $\lambda = 0.936\,\mathrm{mm}$ with probing in a vertical direction through a vacuum chamber center. Time resolution in the measurements performed $\tau \sim 0.2\,\mu\mathrm{s}$. A density level is controlled in real time using a phasemeter signal that is proportional to nl. When processing the signals, additional filtration is used in the phasemeter, which however does not hinder observation of low-frequency oscillations of the linear density. For observing oscillations of the electron density, the present study has used a signal of the intermediate frequency (IF) $f_{\mathrm{IF}} = 5\,\mathrm{MHz}$, which was digitalized at the frequency $f_s = 50\,\mathrm{MHz}$, and the amplitude $A(t)$ and the linear density $nl(t)$, restored therefrom by means of Fourier methods and not additionally filtered. The IF signal is a result of mixing the probing and reference waves of the VHG-interferometer and its amplitude reflects power of recorded probing radiation.

2. Operating limits of the VHF-interferometer as a tool for observing oscillations of the plasma density

Detectability of density oscillations by means of the VHF-interferometer is limited by an installed IF-signal bandpass filter of the bandwidth $\Delta f = 300\,\mathrm{kHz}$ as well as a noise level. The filter has a sharp characteristic with an AFR boundary slope exceeding 200 dB/octave. Presence of the bandpass filter does not directly results in limitation of the frequencies of oscillations that can be determined from a signal of a linear-integrated density nl. Since the IF signal is harmonic, it can be represented as:

$$U_{\mathrm{IF}} = A(t)\cos(2\pi f_{\mathrm{IF}} t + \Delta\varphi + \varphi_0), \tag{2}$$

where $A(t)$ is a signal amplitude, $\Delta\varphi$ is an additional phase incursion induced by the plasma, φ_0 is a phase incursion induced by a difference of interferometer arms lengths. The available filter will suppress frequencies that are spaced from the carrier frequency $f_{\mathrm{IF}} = 5\,\mathrm{MHz}$ by more than $\Delta f/2 = 150\,\mathrm{kHz}$. Presence of such limitations is induced variation of the IF signal phase in time due to presence of variation of $\Delta\varphi/\Delta t$. Thus, it is possible to estimate the limitation of possible $\Delta\varphi/\Delta t$ measured by the interferometer.

$$\left(\frac{\Delta\varphi}{\Delta t}\right)_{\max} = 2\pi\,\frac{\Delta f}{2} = r_e\lambda\,\frac{\Delta(nl)}{\Delta t}. \tag{3}$$

By assuming a harmonic dependence of a small-scale disturbance of the density on time, it is possible to express this disturbance as a certain addition to the main value of the density $(nl)_0$:

$$nl = (nl)_0 + \delta(nl)\cos(2\pi f t). \tag{4}$$

By substituting (4) into (3), it is possible to estimate a frequency limitation to recordability of oscillations of the density m by the VHF-interferometer of T-15MD in a straight script.

$$f \le \frac{1.9\cdot 10^{17}[\mathrm{m}^{-2}]}{\delta(nl)}\,\Delta f. \tag{5}$$

Another factor that limits the oscillation measurement range is an interferometer noise signal that is $\sigma_N = 2\cdot 10^{16}\,\mathrm{m}^{-2}$ [16]. But it is incorrect to directly compare the noise signal with the oscillation amplitude during spectral processing. In order to estimate an oscillation's threshold amplitude, at which it is still possible to distinguish a useful signal against a backdrop of noise, we assume that our initial disturbance is a time signal, whose spectrum is represented by a Gaussian shape:

$$S(f) = A\cdot\exp\left(-\frac{(f-f_0)^2}{2\sigma^2}\right), \tag{6}$$

where f is an oscillation frequency, σ is a mean-square error related to the spectrum full width at half maximum $FWHM = 2\sqrt{2\ln 2}\sigma$, A is an amplitude of the spectrum.

In order to estimate detectability of small oscillations of the density, a Fourier-spectrum of the interferometer phase signal was analyzed in a stationary discharge stage without pronounced MHD-activity, which is noticeable different from the spectrum of the same signal without the plasma. It is noted that spectra of this signal vary in a limited range for discharges from various T-15MD campaigns, thereby making it possible to apply them for estimating detectability of oscillations.

Taking into account that most observed oscillations of the density, which are recorded by the VHF-interferometer of T-15MD, have $FWHM < 1\,\mathrm{kHz}$, we will use this value in order to distinguish a density oscillation amplitude that can be unambiguously defined as exemplified by the

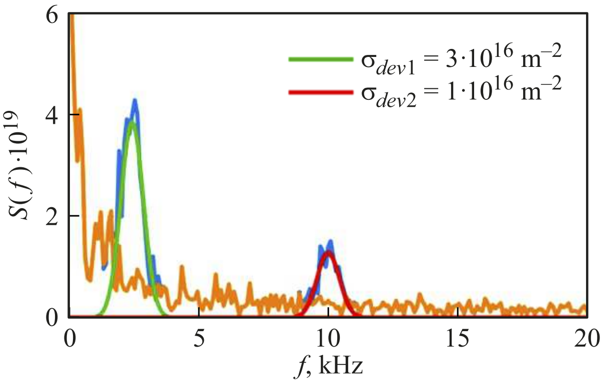

Figure 1. Phase spectrum with superimposed oscillations that have a Gaussian-shaped spectrum. The legend reflects a mean-square error of oscillations, which is recalculated in *nl*.

spectrum of the phase signal in the shot No. 4515. The signal spectrum with two superimposed artificial spectra of oscillations is shown in Fig. 1. The Figure applies the orange color to indicate the spectrum of an experimental signal and the blue color to indicate the summed spectrum with superimposed spectra of oscillations with central frequencies $f_1 = 2.5\,\text{kHz}$ and $f_2 = 10\,\text{kHz}$ and $FWHM = 1\,\text{kHz}$. At the same time, the amplitude for the oscillation with the frequency f_1 is taken to be in 3 times higher than for the frequency f_2, since the low-frequency range (up to 2 kHz) of the spectrum of the experimental signal has high intensity, thereby complicating observation of small-amplitude oscillations.

Based on the value of the linear density $nl \sim 3\cdot10^{19}\,\text{m}^{-2}$, which is matched with the moment of time, for which the spectrum of the linear density signal is constructed, and the two values of the mean-square errors of oscillations $\sigma_{\text{dev1}} = 1\cdot10^{16}\,\text{m}^{-2}$, $\sigma_{\text{dev2}} = 3\cdot10^{16}\,\text{m}^{-2}$ ($\sigma_{\text{dev}} = \sqrt{\frac{1}{n}\sum_i x_i^2}$, i.e. the mean-square error of the signal in a time range in the Gaussian distribution of its spectrum in a frequency range (6)), which can be clearly discerned in the spectrum, it can be concluded that the VHF-interferometer can be used to detect oscillations of the linear density $\delta(nl)/nl \sim 0.03\,\%$. At the same time, this estimate is valid for oscillations of the frequencies $f > 3\,\text{kHz}$, while at the smaller frequencies this value is in times higher. σ_{dev1} and σ_{dev2} are obtained by an inverse Fourier transform for artificial signals shown in Fig. 1, with subsequent determination of the mean-square error in the time range. The value is obtained by dividing the value of σ_{dev1} by the linear density of the plasma at the moment of spectrum acquisition ($nl \sim 3\cdot10^{19}\,\text{m}^{-2}$). The exact value of the recorded amplitude depends on parameters of a discharge and parameters of an oscillation.

Based on these two limiting factors, it is possible to estimate characteristics of oscillations of the linear density, which can be detected by means of the VHF-interferometer (Fig. 2) for the two linear densities: an average value across analyzed discharges — $nl = 2\cdot10^{19}\,\text{m}^{-2}$, while a boundary value of the linear density, which can be measured by the VHF-interferometer, is $nl = 5\cdot10^{19}\,\text{m}^{-2}$ [13].

Fig. 2 shows a range of the low-frequency MHD-oscillations measured by the T-15MD tokamak as well as data for measurement of Alfvén modes in the JET tokamak by means of the microwave interferometer [4], in the DIII-D tokamak by means of the laser interferometer [17] and in the TJ-II stellarator by means of the HIBP diagnostics [18]. This graph demonstrates that the IF-filter at 300 kHz can limit the range of measurement of the high-frequency oscillations ($f > 100\,\text{kHz}$) with a high amplitude exceeding 1 %.

Parameters of the studied plasma discharges of T-15MD are close to plasma parameters in the TJ-II stellarator, while the IF-filter of 300 kHz only partly covers the range of data from TJ-II. Consequently, the IF-filter can hinder observation of Alfvén oscillations in the T-15MD tokamak. However, origination of such instabilities on the interferometer's probing chord would result in heavy attenuation of the IF signal by the amplitude, causing failures in operation of the VHF-interferometer. No such effects were observed in the analyzed experimental data. Nevertheless, using

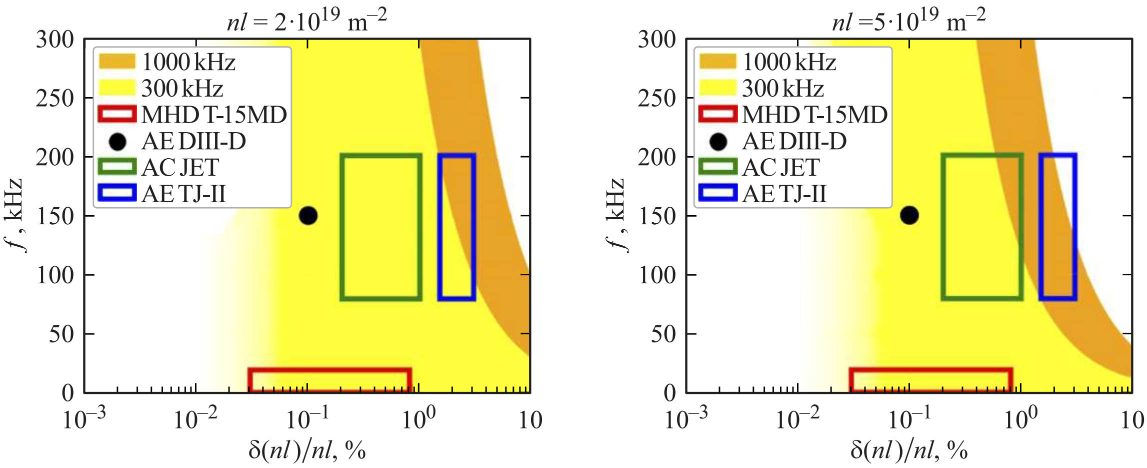

Figure 2. Parameters of oscillations of the density, which are available for measurement using the VHF-interferometer. The yellow color marks an area of measured oscillations when using the 300 kHz IF-filter, while the orange area is for the IF-filter 1000 kHz.

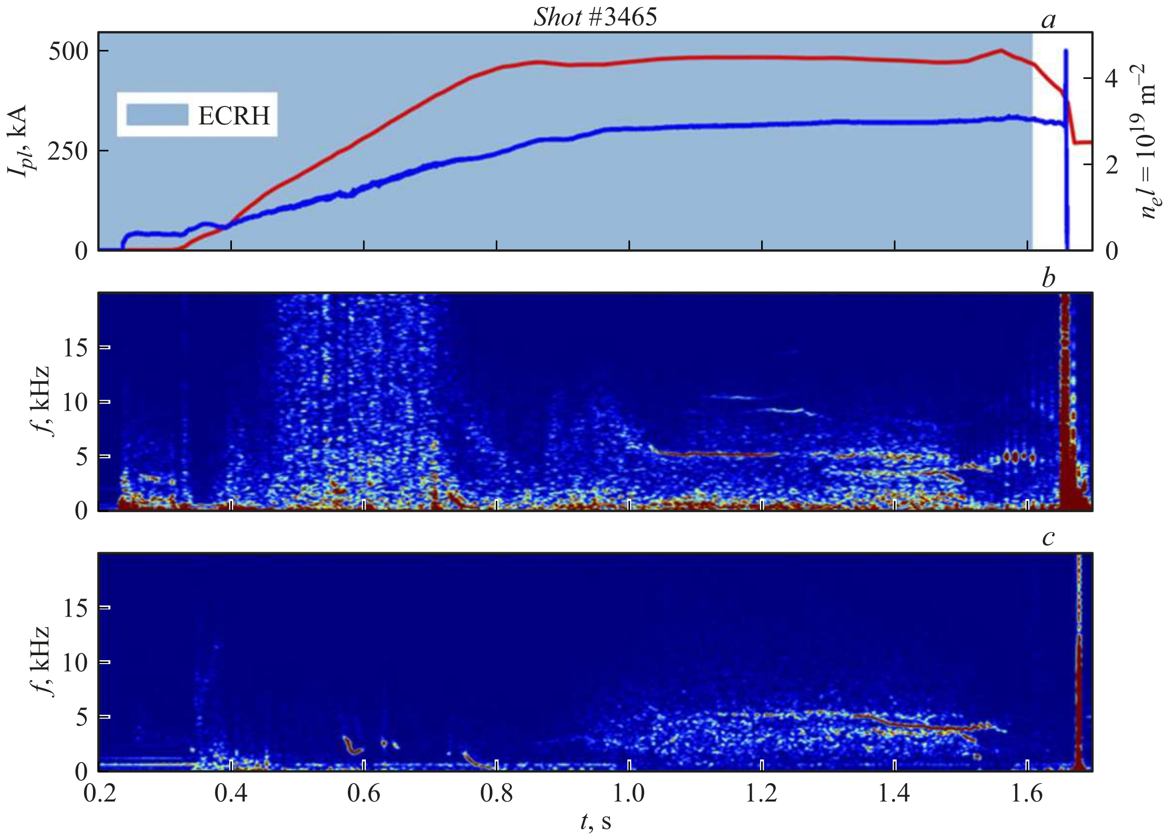

Figure 3. Time evolution of the current and the linear density (a) of the plasma in the shot No. 3465, a spectrogram of the signal of the VHF-interferometer (b) and of the electromagnetic probe (c).

the IF-filter at 1000 kHz potentially will make it possible to extend ranges of measurement of such oscillations. In case of considering the value of the boundary liner density $nl = 5 \cdot 10^{19}\,\mathrm{m}^{-2}$ the range of oscillations available for observation significantly decreases, but it is still possible to measure MHD-oscillations.

Specifically, it is worth noting a limitation to detectability of oscillations in terms of refraction of electromagnetic waves in the plasma. Refraction does not affect the frequency of recorded oscillations, but it can result in inaccuracy of determining the density oscillation amplitude, since when calculating the values of the plasma density a probing trajectory is considered to be rectilinear and refraction results in its curvature. Nevertheless, it is demonstrated in [13] that an error in measuring the electron density due to the refraction effect is just several percent, since at the high values a loss of the signal of the VHF-interferometer would be observed. It is also demonstrated in the study that it is possible to probe the T-15MD plasma by the VHF-interferometer along a vertical channel when the axis density $n_0 = 5 \cdot 10^{19}\,\mathrm{m}^{-3}$. The limits shown in Fig. 2 are considered up to the value of the linear density $nl = 5 \cdot 10^{19}\,\mathrm{m}^{-2}$, which is included in an operating range of the VHF-interferometer, since discharges in T-15MD are characterized by $l > 1$ m for the probing chord of the VHF-interferometer.

3. Results of measurements of the parameters of plasma density oscillations

For experimental data, the present study has analyzed plasma discharges produced during the experimental campaigns of 2024–2025 in the T-15MD tokamak. The studied shots were characterized by wide ranges of the plasma current $I_{pl} = 200{-}620$ kA and the linear density $nl = 1{-}3 \cdot 10^{19}\,\mathrm{m}^{-2}$. Duration of the discharges was $t = 500{-}2000$ ms. All the discharges included preionization and subsequent heating by means of a gyrotron of power of up to 1 MW with the frequencies 82.6 GHz (the 2024 campaign) and 105 GHz (the 2025 campaign). The spectrograms of the VHF-interferometer were verified using additional data obtained from electromagnetic diagnostics (EMD) of the T-15MD tokamak [19] as well as from a soft X-ray diagnostics system (SXR) [20].

Fig. 3, a shows time evolutions of the main parameters of the discharge in the shot No. 3465. During the discharge, the signal of the VHF-interferometer exhibited low-frequency MHD-oscillations (Fig. 3, a), which were also recorded by MHD probes of the T-15MD tokamak (Fig. 3, b). The spectrograms of both the diagnostics exhibit plasma oscillations at the frequency 5–6 kHz, which corresponded to an MHD-disturbance with a poloidal mode number $m = 3$ [21].

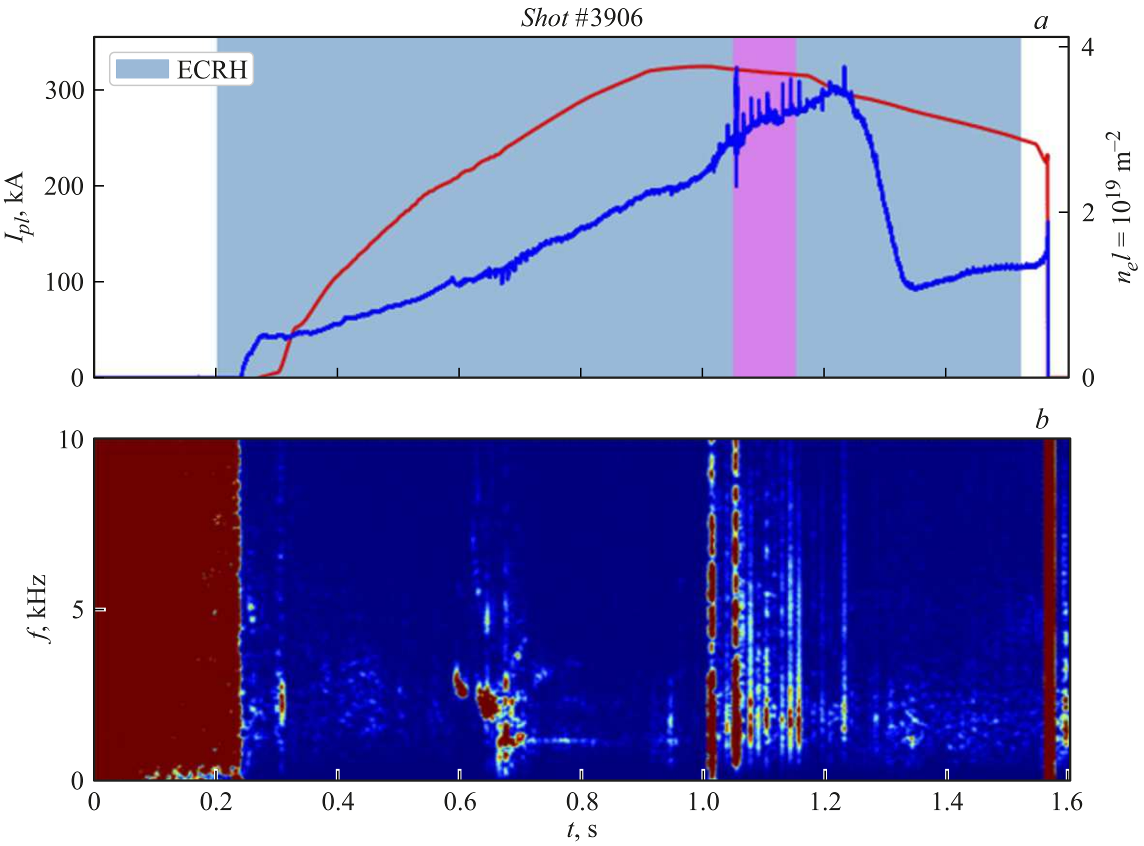

Figure 4. Time evolution of the plasma parameters in the shot No. 3906 (*a*) and the spectrogram of the signal of the VHF-interferometer (*b*).

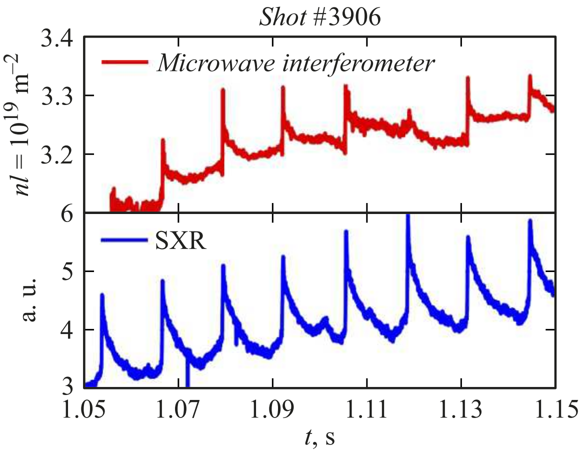

Figure 5. Sawtooth oscillations in the signal of the VHF-interferometer and the signal of the SXR channel, which is transmitted through a central area of the plasma cord.

Besides, the spectrogram of the VHF-interferometer shows presence of higher-high-frequency plasma disturbances with the frequency exceeding $f = 10$ kHz, which are not observed in the EMD signals.

The shot No. 3906 exhibited sawtooth oscillations that were also observed in the signal of the VHF-interferometer of the T-15MD tokamak. Fig. 4 shows a progress of the current and the linear density of the plasma (Fig. 4, *a*) of the discharge No. 3906 as well as the spectrogram of the signal of the VHF-interferometer (Fig. 4, *b*).

For the time period $t = 1.05-1.15$ it shows a signal of the linear density of the VHF-interferometer (Fig. 5, *a*) and a signal of the soft X-ray diagnostics channel (SXR) (Fig. 5, *b*). A period of the observed sawtooth oscillations $T \sim 13$ ms, the value of the density oscillations was up to $\delta(nl)/nl \sim 5\,\%$.

The experimental data were analyzed to demonstrate that the VHF-interferometer was used to detect MHD-disturbances in the frequency range $f < 15$ kHz and with the value of the plasma density oscillation $\delta(nl)/nl \sim 0.03\,\%-5\,\%$.

Due to recording the IF signal in the system of the VHF-interferometer of the T-15MD tokamak, it is possible to analyze both the data on the linear electron density of the plasma (the signal phase) as well as the IF amplitude. It has been found when processing the experimental data that for some plasma shots spectral analysis of the signal amplitude makes it possible to obtain additional information about disturbances of the linear electron density of the plasma. Fig. 6 shows the spectrograms of the linear density and the IF-signal amplitude for the shot No. 3453. The amplitude spectrogram exhibited disturbances that are not observed in

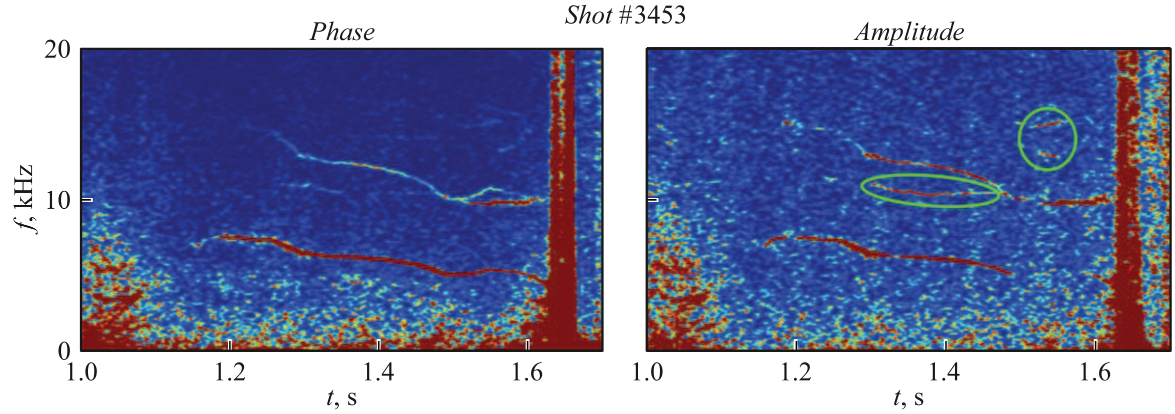

Figure 6. Spectrograms of the phase and the amplitude of IF for the shot No. 3453. The green color marks disturbances that are observed in the signal amplitude only.

the spectrogram of the linear density. These specific features can be related to effects due to refraction and variation of polarization of the probing wave due to the Faraday effect, which noticeably affect exactly power of the recorded wave of the VHF-interferometer.

Conclusion

We have studies capabilities of the VHF-interferometer of the T-15MD tokamak for analysis of oscillations of the linear electron density of the plasma. The operating limits of the diagnostics have been estimated. The experimental data have been analyzed to demonstrate that using the VHF-interferometer makes it possible to record the low-frequency MHD-oscillations within the range of up to 15 kHz with relative disturbances of the density within the range $\delta(nl)/nl \sim 0.03\,\%{-}5\,\%$. It is also found that spectral analysis of the signal amplitude of the VHF-interferometer makes it possible to obtain additional information about plasma disturbances, thereby extending diagnostics capabilities.

It is demonstrated that the current IF-filter with a 300 kHz bandwidth does not limit measurement of low-frequency oscillations (up to 50 kHz) within the wide range of the amplitudes. However, at the frequencies above 100 kHz, for example, in case of the Alfvén modes, the filter can suppress a signal with high relative disturbances $\delta(nl)/nl > 1\,\%$, which can hinder their recording. Using the IF-filter with the wider bandwidth will potentially make it possible to expand the diagnostics capabilities for recording the high-frequency oscillations when signs thereof appear in the signals of the VHF-interferometer.

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Conflict of interest

The authors declare that they have no conflict of interest.

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