Alfvén waves in ohmic plasma of the TUMAN-3M tokamak

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Abstract. Properties of Alfvén waves (AWs) are studied which were excited in ohmic plasma of the TUMAN-3M tokamak. By means of matching the AWs frequency calculated from electron density profile with the experimentally measured one, it was found that the waves are localized in the region of $r/a < 0.5$. The effect of the impurity carbon ions on AWs frequency has been studied. It has been experimentally confirmed that, in the case of fully ionized carbon ions, when mass-to-charge ratios are equal for both the dominant and impurity ions, the AWs frequency does not depend on the impurity density, and is determined by the plasma electron density and the mass of dominant ions.

1. Introduction
The studies of the Alfvén waves physics are of great importance because the development of the Alfvén waves in tokamak plasmas increases the fast ions loss, thereby reducing the plasma heating efficiency. In particular, at the COMPASS [1] and TUMAN-3M [2–4] tokamaks, it was found that AWs generation is not always associated with the presence of suprathermal ions, since AWs may be excited in the ohmic plasma. Therefore, AWs properties should be studied in the ohmic heating (OH) regime as well. The first experimental observations of AWs in the TUMAN-3M [5] tokamak and confirmation of the Alfvén nature of those waves were reported in [2, 3]. Some characteristic features of AWs in plasma of the TUMAN-3M tokamak are described in [2–4, 6]. In [4], the possible mechanisms of AWs excitation in the OH plasma with no fast ions are discussed. In [6], the method for determining the AWs localization used in this study is described in detail.

2. Determination of the Alfvén waves localization
One of the important parameters of AWs is their localization in the poloidal cross section of the tokamak plasma. In particular, this information is required to identify the type of the excited Alfvén modes. In some tokamaks, for example, in the COMPASS tokamak [1], AWs are localized at the plasma edge; in the Globus-M tokamak [7], AWs are also localized at the plasma periphery in a narrow region on the low field side from the plasma axis, and this, in combination with other data, allows interpreting them as Toroidal Alfvén Eigenmodes (TAE). To determine the AWs localization in the Globus-M tokamak, the microwave Doppler backscattering diagnostics was used [7]. However, at the TUMAN-3M tokamak, this diagnostics failed to detect AWs. Apparently, they were localized too deep inside plasma and/or their amplitude was too small. Even in the first experiments on the AWs investigation at the TUMAN-3M [2], we have assumed the AWs central localization. In particular, this assumption was based on the observed correlations between the bursts of AWs generation and
sawtooth oscillations [3]. To verify the assumption of the AWs central localization, a method described in [6] has been applied. The AWs localization was determined by matching the AWs frequency measured with the help of a fast magnetic probe installed inside the vacuum chamber with the calculated one. The AWs frequency was calculated using the dispersion relation \( f = v_A k / 2\pi \) and the experimentally measured electron density profile. Time dependences of the local densities were obtained applying the Abelian transform to the chord-averaged density profiles measured by the multichannel microwave interferometer. Deviation of the calculated frequency from the experimentally measured one was minimized by selecting the parallel wave number \( k || \), which was a free parameter. The OH shots with deuterium used as plasma-forming gas in which L – H transitions were observed were chosen for analysis, since, in this scenario, there is a significant change in the density profiles due to the transport barrier formation. The calculated frequencies in the supposed region of AWs excitation (solid curves) and the experimentally measured ones (squares) are compared in Figures 1a and 1b.

![Figure 1a](image-a.png)  
![Figure 1b](image-b.png)  
![Figure 1c](image-c.png)  
![Figure 1d](image-d.png)

**Figure 1.** (a) and (b) time dependences of AWs frequencies. Squares and solid curves correspond to the frequencies measured by a fast magnetic probe and those calculated from the local densities in increments of \( r = 2 \) cm, respectively; (c) the sum of squares of the frequency differences as a function of plasma radius for several longitudinal wave numbers. (d) AW frequency as a function of the Alfvén velocity.

Figure 1a demonstrates the central localization of AWs for the chosen \( k || \) value, while, for another \( k || \) value, AWs in the same shot became edge-localized, as it can be seen in Figure 1b. These localizations (inside the region with a radius of \( r \approx 6 \) cm and at the plasma periphery at a radius of...
$r = 22 \text{ cm}$) seem to be the most probable. Figure 1c illustrates this. It can be seen that, in the analyzed shot, the calculated frequency optimally matches with the experimental data at $k_l = 1.74 \text{ m}^{-1}$ and $r = [0 \text{ to } 6] \text{ cm}$ $\text{SUM} = 0.11 \times 10^{-2}$ MHz$^2$ as well as at $k_l = 0.80 \text{ m}^{-1}$ and $r = 22 \text{ cm}$ $\text{SUM} = 0.15 \times 10^{-2}$ MHz$^2$. In the intermediate radial range of $6 < r < 20 \text{ cm}$, the coincidence is worse. The following fact speaks in favor of the AWs central localization. Distortion of the linear dependence of the AWs frequency on the AWs velocity reported in [3] is not observed if, in calculations the AW velocity, the central local plasma densities in the region of AWs propagation are used instead of the chord-averaged (or peripheral) ones. Figure 1d demonstrates this. Triangles correspond to the AWs velocities calculated using the chord averaged densities; there is some uncertainty in choosing the scaling, which can be explained by different density profiles in the L and H modes. This uncertainty is eliminated when the central densities are used (circles). Squares correspond to the AWs velocities calculated using the edge densities (at $r = 22 \text{ cm}$). In this case, the error of linear approximation is higher. In addition, the following estimate evidences against the edge localization of AWs. If AWs truly had edge localization, they would not be TAE. It follows from the relation which is valid for TAE: $f_{\text{TAE}} = v_A/4\pi R q$ [8]. If we take $v_A = 8 \times 10^6 \text{ m/s}$ (see Figure 1d), $R = 0.53 \text{ m}$ and $q = 4$ at $r = 22 \text{ cm}$, we will obtain $f_{\text{TAE}} = 0.3 \text{ MHz}$, which is considerably less than the experimentally measured frequency $f = 0.8 \text{ to } 1.0 \text{ MHz}$. Thus, on the basis of the analysis given above, it can be concluded that, in the OH operating mode of the TUMAN-3M tokamak, AWs are localized in the central region within a radius of $r/a < 0.5$.

3. Alfvén waves in deuterium plasma with increased carbon impurity content
It is known that the AWs frequency in multi-component plasma depends on its mass density $f \sim \left( \sum m_\beta n_\beta \right)^{-0.5}$ [8, 9]. In principle, that allows indicating the presence of impurity in plasma by determining the shift in the AWs frequency relative to that in pure plasma. In a series of experiments at the TUMAN-3M in which the carbon content in plasma was increased, this method was tested. The carbon content can be qualitatively characterized by the intensity of CIII line emission. Figure 2 demonstrates an increase in the CIII line emission intensity by approximately 17 times in a typical shot with carbon-contaminated deuterium plasma (curve b) as compared to a shot with pure deuterium plasma with $Z_{\text{eff}} = 1$ (curve a).

![Figure 2](image.png)

**Figure 2.** Intensity of the CIII line emission normalized to the chord-averaged electron density.

![Figure 3](image.png)

**Figure 3.** Spectra of AWs bursts measured by a fast magnetic probe.
As follows from the dependence $f \sim (m_D n_D + m_C n_C)^{-0.5}$, the presence of an impurity should lead to a decrease in the $f$ frequency. In experiments with carbon-contaminated deuterium plasma, the AWs frequency has really decreased, but since the plasma density has also changed, a direct comparison of frequencies is incorrect. Therefore, it is interesting to clear up the real causes for the decrease in the AWs frequency in plasma with increased carbon content.

Not all the necessary experimental data were available in a single plasma shot, so three shots were chosen for the analysis: #17112910, 17112810 and 17112912. First, in the steady state discharge stage, the plasma effective charge $Z_{\text{eff}}$ was calculated using the Spitzer formula, neglecting the inductive additive to the loop voltage. The electron temperature profile was measured by the soft X-ray (SXR) diagnostics which uses the foil-absorption technique. It is reasonable to assume that, in the core plasma, carbon atoms are completely ionized since the electron temperature at the plasma axis is considerably high $T_e(0) \approx 500$ eV [10]. As a result, for shot #17112912, the plasma effective charge was found to be $Z_{\text{eff}} = 5.1$, and the relative ions densities were $n_{i\text{D}}/n_e = 0.16$, and $n_{i\text{C}6+}/n_e = 0.14$. For several typical shots in contaminated plasma, the plasma effective charges were in the range of $Z_{\text{eff}} = 4.1-5.4$, which qualitatively agrees with the observed increase in CIII emission. Let us consider two shots to demonstrate the effect of an increase in the plasma effective charge on the AW frequency: shot #17112910 with highly carbon-contaminated deuterium plasma and shot #17013109 with pure deuterium plasma. The parameters of the shots under study are presented in Table 1, where $\Delta t$ is time window for the spectrum reconstruction (Figure 3). Figure 3 shows the spectra of the AWs bursts: (a) in pure deuterium plasma and (b) in deuterium plasma with increased carbon content. The difference in the amplitudes of the AWs spectra can be explained by the difference in the plasma densities. Previously, in the experiments at the TUMAN-3M tokamak, it was ascertained that the higher is the plasma density, other parameters being the same, the lower is the amplitude of the oscillations and the less is the number of the AWs bursts. AWs disappear at densities higher than $n_e \approx 3 \times 10^{19} \text{ m}^{-3}$.

| Plasma species | Shot no. | $\Delta t$, FFT time window, ms | $f$, MHz | $\bar{n}_e$, $10^{19}$ m$^{-3}$ | $B_t(0)$, T | $I_{pl}$, kA |
|----------------|----------|-------------------------------|--------|----------------|----------|-----------|
| D+C$^{6+}$     | 17112910 | 53.28-53.38                   | 0.873  | 1.5           | 0.87     | 145       |
| D              | 17013109 | 54.76-54.86                   | 1.070  | 0.8           | 0.87     | 145       |

Having determined the concentration of fully ionized carbon $n_{e\text{C}^{6+}}$ from the calculated plasma effective charge $Z_{\text{eff}}$, one can also determine the changes in the AWs frequency $f$ for these two discharges. Namely, $f_{\text{DC}}/f_{\text{D}} = 0.74$, where $f_{\text{DC}}$ is the AWs frequency in the plasma with increased carbon content, $f_{\text{D}}$ is the AWs frequency in pure deuterium plasma. The same ratio was obtained for the experimentally measured frequencies $f_{\text{DC}}^{exp}/f_{\text{D}}^{exp} = 0.82$. As a result, it turned out that the frequency calculated using the formula for the Alfvén velocity is in good agreement with the experimentally measured one, if, in calculations, we use the concentration of fully ionized carbon ions determined according to the Spitzer formula.
We note that, in the case of deuterium plasma, at the same $B$ and $n_e$ values, the presence of $C^{6+}$ ions has no effect on the $f$ frequency: 
$$\frac{f_{D+C}}{f_D} = \frac{B_z(D+C)}{B_z(D)} \left( \frac{n_e(D)}{n_e(D+C)} \right)^{0.5}.$$ 
In other words, it is impossible to detect the presence of impurity in deuterium plasma using the AWs frequency measurements. It follows from the formula $f \sim \left( \sum m_i n_i \right)^{-0.5} = \left( m_\text{D} n_\text{e} + n_z (m_z - Z \text{m}_\text{D}) \right)^{-0.5}$, where the corresponding term becomes zero $m_z - Z \text{m}_\text{D} = 0$ at $Z = m_z/m_\text{D}$. Thus, in the case when mass-to-charge ratios are equal for both plasma-forming and impurity ions (for example, $C^{6+}$ or $O^{8+}$ ions in deuterium plasma), the AWs frequency does not depend on the impurity concentration. It is determined only by the plasma electron density, magnetic field and atomic mass of the plasma-forming ion. This problem was investigated numerically in [11]. Therefore, it is impossible to detect the presence of such ions in plasma using only the data on the AWs spectra without additional information.

On the other hand, the obtained result can be considered as confirmation of the fact that, in the described experiments, carbon ions were almost completely ionized: the estimate of the AWs frequency for the carbon-contaminated plasma (shot # 1711291), performed according to formula $f = k_1 v_A/2\pi = k B_z(0)/2\pi \sqrt{\mu_0 \text{m}_\text{D} n_\text{e} (r = 10 \text{cm})}$ at $k_1 = 1.74 \text{m}^{-1}$, gives the value $f = 0.858$ MHz. The experimentally measured frequency in this shot is $f = 0.873$ MHz, so there is a good agreement: the difference between the calculated frequency and the experimental one is ~2%.

4. Conclusions

Thus, in this paper, we have ascertained that, in OH plasma of the TUMAN-3M tokamak, the AWs are localized near the plasma axis within a radial range of $r/a < 0.5$. A broad range of the AWs localization may indicate that the AWs under discussion are the Global Alfvén Eigenmodes (GAE). The studies of the effect of the carbon impurity concentration on the AWs frequency have shown that it is possible to determine the impurity concentration $n_z$ (and, consequently, to calculate the plasma effective charge $Z_{\text{eff}}$) from the AWs frequency $f_\lambda$ only if the mass-to-charge ratios of the plasma-forming and impurity ions are not equal: $Z/A(\text{main species}) \neq Z/A(\text{impurity})$. Good agreement of the experimentally measured frequency and the one calculated using the plasma electron density data indicates that the carbon ions (carbon is the main impurity in the shots under consideration) were completely ionized.

Acknowledgments

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