Plasma composition determination from Alfvén wave spectra in ohmic discharges on the TUMAN-3M tokamak

G.I. Abdullina, L.G. Askinazi, A.A. Belokurov, F.V. Chernyshev, V.A. Kornev, S.V. Krikunov, S.V. Lebedev, A.D. Melnik, D.V. Razumenko, P.V. Reznichenko, A.I. Smirnov, A.S. Tukachinsky, N.A. Zhubr

Ioffe Institute, St. Petersburg, Russian Federation

Measurement and control of plasma composition (PC) is among the key tasks of the future tokamak-based fusion reactor operation. One of the promising methods of PC determination is based on the analysis of Alfvén wave (AW) spectra, which depends on the mass density of the plasma. This work presents the results of experimental study of AW spectra in ohmic discharges on the TUMAN-3M tokamak. The AWs with frequencies in the range of 600-2100 kHz develop in the discharges with line average density generally lower than $1.5\times10^{19}m^{-3}$ [1–4]. AWs in the absence of fast ions can be related to runaway electrons [3]; particularly, they may be driven by toroidal precession of barely trapped high energy electrons [5]. Also, they may be caused by shock excitations during magnetic reconnections [6]. Experiments with excitation of AWs for plasma diagnostics were performed on the JET [7] and on the TCABR [8] tokamaks.

In the experiments on the TUMAN-3M tokamak, two types (hydrogen-deuterium and hydrogen-helium plasmas) of two-component plasmas were investigated to explore the possibility of measuring PC from AW spectra. This choice of plasma components is due to their different charge-to-mass ratio Z/A, for example, Z/A(He^{2+}) = 1/2, Z/A(H^{+}) = 1. This makes possible to determine PC by measuring AW frequency [9].

Hydrogen-deuterium plasma. Two scenarios were used in the experiments: deuterium puffing into hydrogen background plasma and hydrogen puffing into deuterium background plasma. The isotope ratios, i.e. relative concentrations of hydrogen $n_\mathrm{H}/(n_\mathrm{H}+n_\mathrm{D})$ or deuterium $n_\mathrm{D}/(n_\mathrm{H}+n_\mathrm{D})$ in the mixed hydrogen–deuterium plasma obtained from AW spectra were in qualitative agreement with the results of spectroscopic and charge-exchange (CX) flux measurements [9].

Hydrogen-helium plasma. The hydrogen-helium plasma requires a more complicated analysis than the simple one performed in [9] for the hydrogen-deuterium mixture due to the presence of two ionization states of helium. Let us compare two hydrogen-helium discharges with plasma parameters: plasma current I_pl = 146 кA, toroidal magnetic field B_T = 0.98 T. Scenario of working gases puffing in discharge 20092408 (hereinafter referred to as #8): 0 – 4 ms - hydrogen pre-puffing, 1 – 21 ms – helium puffing. Discharge 20092410 (hereinafter referred to as #10) differs from #8 by the extra hydrogen puffing performed from 70 to 96 ms. Different valves were used to inlet hydrogen and helium. The hydrogen puffing was performed through valve located at the low field side (LFS-valve). The hydrogen flow was controlled by the photodiode which registered the light emitted in a visible wavelength range (Balmer H-alpha line dominantly) in the vicinity of the LFS-valve. Magnetic perturbations caused by AWs were recorded using the in-vessel magnetic probe located in Scrape-Off Layer (SOL) near the vacuum vessel (~0.5 cm from the wall) at 11 degrees above the outer equatorial plane. Spectrograms of the magnetic probe signals in #8 (Fig. 1a) and #10 (Fig. 1b) illustrate the AW's existence in the form of individual bursts from 45 to 105 ms in the frequency range 780–1200 kHz. Time evolution of AW frequency can be approximated by one curve in both discharges up to 70 ms (dashed line). Since 70 ms, #10 exhibits a steeper decline of AW frequency compared with one in #8. Figure 1c shows f_A – the AW frequencies found by approximation of the AW bursts' frequencies. Electron density was measured by microwave interferometer with 10 vertical channels. Central electron density $n_e(0)$ was reconstructed using the Abel transform of the chord measurement data, see Fig. 1d.

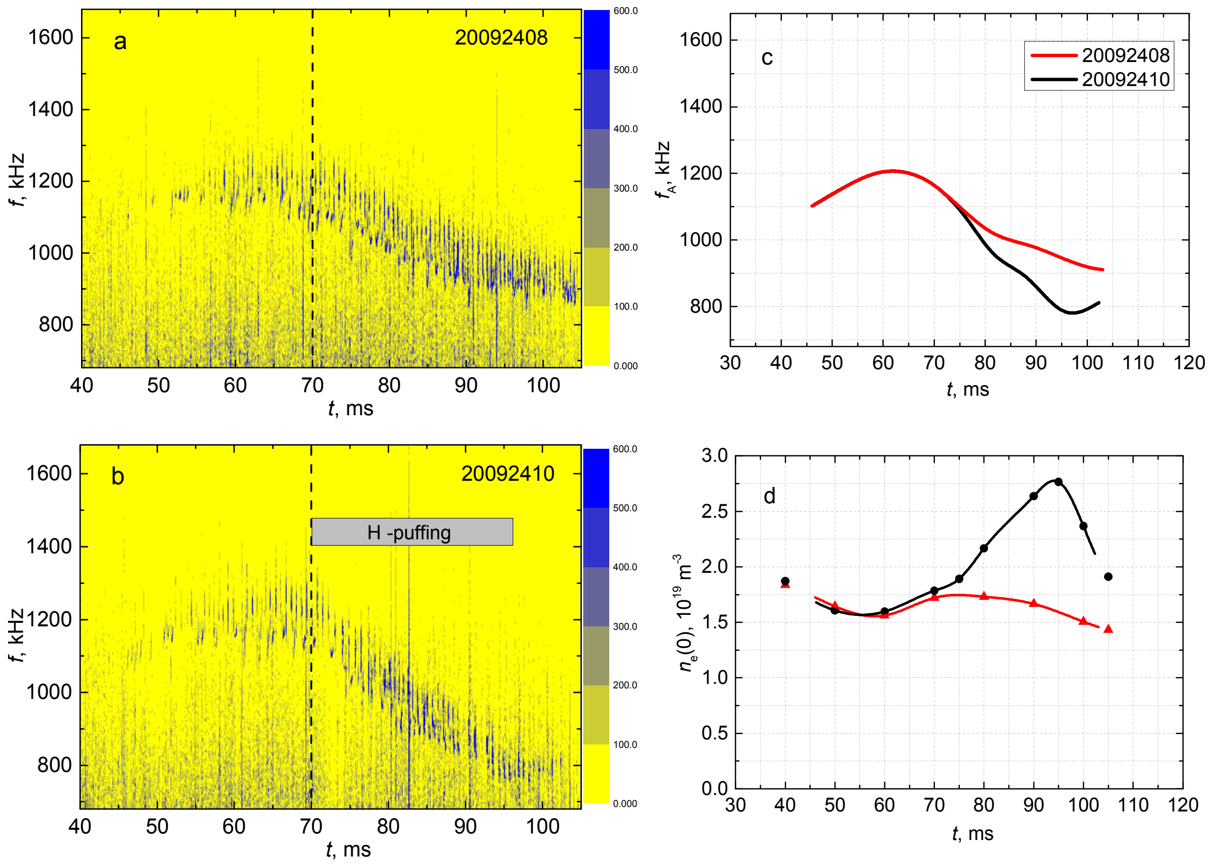

Figure 1. a, b – Spectrograms of magnetic probe signals; c – Approximation of AW bursts by curves; d–Central electron density $n_e(0)$.

In the central plasma area $0 < r < 6$-10 cm - the region of AW location [4] - electron temperature T_e exceeds 400 eV (a = 22 cm, T_e(r = 0 cm) ≥ 500 eV, T_e(r = 10 cm) ≥ 400 eV). Helium is fully ionized at these temperatures since the second ionization potential of helium is 54 eV. Then the condition of quasi-neutrality for the central plasma area has the form: $n_{H^+} + 2n_{He^{2+}} = n_e$, where n_{H^+} and $n_{He^{2+}}$ are densities of hydrogen and fully ionized helium. Ionization symbols will be omitted for simplicity below, assuming that fully ionized helium is considered. Using the plasma quasi-neutrality condition and the dispersion relation for shear AW, we can write the expression for hydrogen density: $n_H = \left(k_{\|}^2 B_T^2 / \left(4\pi^2 \mu_0 f_A^2\right) - 0.5 m_{He} n_e\right) / \left(m_H - 0.5 m_{He}\right)$, where μ_0 is magnetic constant, m_H and m_{He} are hydrogen and helium masses, $k_{\|}$ is the wavenumber component parallel to the magnetic field, the value of which $k_{\|}$=1.74 m^{-1} [4] was taken for the both discharges. Note that under these experimental scenarios it is impossible to select a certain value of $k_{\|}$, which is determined by PC at a particular time instant, as was done for the cases of hydrogen – deuterium plasmas [9], where $k_{\|}$ acted as a free parameter and was chosen so that the isotope ratios were equal to 1 before the onset of pulsed puffing of isotope different from background plasma. Helium density can be found from: $n_{He} = 0.5\left(n_e - n_H\right)$. Figure 2b shows n_{He}/n_H - relative helium density which starting from 70 ms begins to noticeably differ in two compared discharges: it is lower in #10 with hydrogen puffing than one in #8.

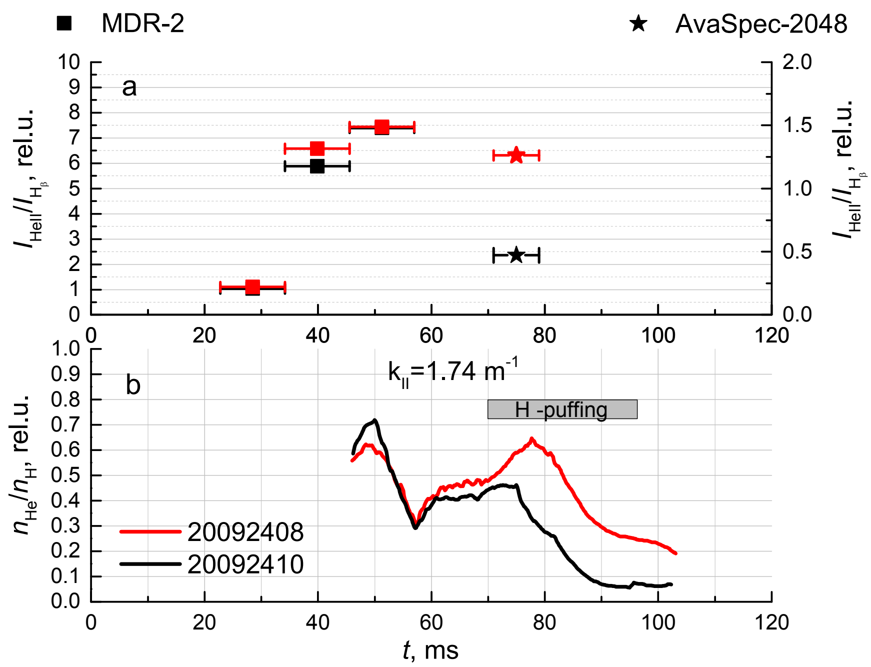

Figure 2. a–Spectroscopic measurements; b–Relative density of fully ionized helium obtained from AW spectra.

Spectroscopic measurements of HeII = 468.57 nm and H_β = 486.13 nm lines intensities were carried out using two devices which view at two different plasma regions along different radial chords. The MDR-2 spectrometer with 20 Å/mm dispersion equipped with CCD camera (87 FPS) was used for measurements at the early phase of the discharges (subsequent measurements proved to be difficult due to high HXR level). Measurements performed with the AvaSpec-2048 spectrometer with 192 Å/mm dispersion and 8 ms exposition time (a single frame per discharge) made it possible to determine $I_{HeII}/I_{H\beta}$ – ratio of HeII and H_β line intensities at 75 ms. In Figure 2a the data on $I_{HeII}/I_{H\beta}$ ratio obtained with MDR-2 (left scale in fig. 2) and with AvaSpec-2048 (right scale) are presented. In the initial phase of the both discharges the $I_{HeII}/I_{H\beta}$ ratio is the same up to 57 ms. Later, at 75 ms these ratios differs for the two discharges: $I_{HeII}/I_{H\beta}$ (#8) = 1.3, $I_{HeII}/I_{H\beta}$ (#10) = 0.5, which reflects additional hydrogen supply in # 10, compared to #8. Relative helium density derived from AW frequency at time interval 71-79 ms (corresponding to AvaSpec-2048 exposition interval): n_{He}/n_H (#8) = 0.55, n_{He}/n_H (#10) = 0.37, see Fig. 2b. Thus, at 75 ms in the plasma central region (region of the AW location) the hydrogen density in discharge #10 is ~1.5 times higher in comparison with #8. This result does not contradict the spectroscopic measurements described above.

Discussion and conclusion. The advantages of the approach of determining PC from AW spectra are simplicity and possibility of determining PC in central plasma regions at low density when high level of HXR emission makes the measurements difficult for the other diagnostic tools. The method has limitations: numerous impurities cannot be taken into account in such simple consideration; it is also necessary to know the region of AW location.

Acknowledgements. The study of AWs was supported by Ioffe Institute in the framework of State Order 0034-2021-0001.The experiments on the TUMAN-3M tokamak were supported by Ioffe Institute in the framework of State Order 0040-2019-0023.

References:

1. Askinazi L.G., Afanasyev V.I., Altukhov A.B. et al // Nucl. Fusion. 2015. V. 55. 104013.
2. Lebedev S.V., et al // 43rd EPS Conf. on Plasma Physics. 2016. P5.036.
3. Tukachinsky A.S., et al // Tech. Phys. Lett. 2016. V.42. 1167.
4. Bakharev N.N., G.I. Abdullina, V.I. Afanasyev et al // Nucl. Fusion. 2019. V.59. 112022.
5. Chu N., Sun Y., Gu S. et al // Nucl. Fusion.2018. V. 58. 104004.
6. McClements K.G. et al // Nucl. Fusion. 2002. V. 42. 1155.
7. Testa D., Blanchard P., Panis T. and JET Contributors // Nucl. Fusion. 2015. V. 55. 123010.
8. Puglia P. G. P. P., Elfimov A. G., Ruchko L. F. et al // Physics of plasmas. 2014. 21. 122509.
9. Abdullina G.I., Askinazi L.G., Belokurov A.A.et al // Tech. Phys. Lett. 2019. V.45. 790.