Experimental studies of the registration of Alfvén wave resonances in the TCABR tokamak by the frequency scanning reflectometry

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Abstract
The experimental studies of the application of the frequency scanning microwave reflectometry to the analysis of the local Alfvén wave (AW) resonances are presented. These resonances are excited close to the magnetic surfaces, at which the local plasma Alfvén velocity $V_A(r) = \frac{B}{\sqrt{\mu_0 m_r n_i(r) M_{\text{eff}}}}$ is equal to the phase velocity of the electromagnetic wave, which is excited by the AW antenna system. These AW resonances manifest themselves as spatially radially localized plasma density oscillations at the AW frequency, and can be registered by the microwave scanning reflectometer technique. The experiments in the TCABR tokamak were carried out with the excitation of the AW modes $M=\pm 1, N=\pm 1, \pm 2, \pm 3$ at the frequency $f=4.5$ MHz. It is shown that the modulation of the reflectometer output signal at the AW frequency is increased when the position of the local Alfvén resonance is close to the plasma zone where the reflectometer microwave signal is reflected. The continuous sweeping of the reflectometer frequency in the course of the plasma discharge makes it possible to track the Alfvén zone position.

Introduction
Nowadays the microwave reflectometry is routinely used for probing the structure of magneto hydrodynamic and turbulent fluctuations in fusion plasmas due to their sensitivity to plasma density oscillations in the cutoff layer. Wide possibilities of this diagnostic technique can be realized by integrating it with AW excitation by external antennae. In this case coherent plasma density oscillations are excited in predefined plasma regions, and the registration of the related perturbations by the reflectometry technique can be used for diagnostic purposes.

The magnitude of plasma density oscillations in the course of the AW excitation has maximum value in the vicinity of the AW resonance layer. Its position can be found from the equation $\omega_{\text{RF}}^2 = k_{\|}^2(r) C_A^2(r)(1 - \frac{\omega_{\text{RF}}}{\omega_{ci}})$, where $k_{\|}(r) = \left(\frac{N}{R} \left[1 + \frac{M}{N q(r)}\right]\right)$. (Here $\omega_{ci}$ is the effective cyclotron frequency taking into account impurities). The numerical calculations show that the density fluctuations are concentrated within few ion gyroradii of the resonance layer. It is seen that the localization of this zone depends both on the
frequency $\omega_{RF}$ and wave numbers $M, N$ of the excited wave, and on the local plasma parameters $n_e(r), q(r), M_{eff}$. In the case of the O-mode reflectometer the AW dispersion in the plasma region, where the reflectometer signal is reflected, can be simplified [1]

$$\frac{N}{R}\left[1 + \frac{M}{N q(r_d)}\right] \sqrt{\frac{m_e}{m_i M_{eff}}} = \omega \frac{\omega_{RF}}{c_0 c_e \left(1 - \frac{\omega_{RF}^2}{\omega_{ci}^2}\right)}$$

It is seen that this expression does not depend on the plasma density explicitly, but only implicitly through $q(r_d)$. This fact helps us to identify the excited mode numbers $M, N$ and to find the $q(r)$ values. For example, if plasma density increases in the course of discharge, the AW resonance zone moves to the plasma boundary, where $q(r_d)$ is larger. In this case, if AW modes with $M/N > 0$ are excited, the reflectometer will detect the increased AW modulation of the reflected signal at lower frequencies $\omega$. This effect is not present for AW mode with $M=0$, which can be excited due to the toroidal effects.

**Experimental setup**

The experiments were carried out in the tokamak TCABR ($a=0.18m, R=0.61m, B = 1.1T$). The basic parameters in this investigation were the following. Plasma current: $I_p = 70 - 95kA$; edge safety factor: $q(a) \approx 3.1 - 4$; line averaged plasma density: $<n_e> = (0.9 - 1.5) \times 10^{19} m^{-3}$; working gas: hydrogen. In the basic regime of operation, the AW antenna straps in the same toroidal cross-sections are fed by RF currents with $(0, \pi)$ phasing so that they can excite mainly the modes $M = \pm 1, N = \pm 1, \pm 2$. The RF power absorbed by the plasma was limited to $P_{RF} \leq 40kW$.

![Fig.1 Schematic representation of the reflectometer diagnostic scheme: 1- microwave oscillator, f=16-25.5 GHz, 2 - attenuator; 3 - directional coupler; 4 - diode detector; 5 - amplifier; 6 - phase shifter; 7 - resonance amplifier; 8 - horn antenna; 9 - RF Alfvén antennae, 10 - plasma column.](image)

The registration of the AW driven density oscillations was carried out by a microwave reflectometer, which was developed in IST/CFN (Lisbon, Portugal), and operates at the frequency band of 16 to 25.5 GHz. Its scheme is shown in Fig.1.

These rather low frequencies have limited the operational regimes of TCABR to low plasma densities, and only the plasma periphery was studied. The reflectometer was
adapted to the AW experiments in the TCABR. In order to register small signals in the AW frequency band, additional high sensitive selective amplifiers were constructed.

The output signal from the diode (4) is amplified by the wide band amplifier (5) and then is divided into two parts. One part is directed to VME through the low pass filter. This signal is used for plasma radial profile reconstruction. Second part is amplified by the selective amplifier (7) with pass-band frequency $f=(4.5\pm0.5)$ MHz, which corresponds to the excited AW frequency. Then this signal is rectified, integrated with $\tau_{RC}=5\mu\text{sec}$ and acquired by the VME. The VME sampling frequency was $f_s=3$ MHz. The data analysis includes the determination of the amplitude and spectral characteristics of these signals and their dependence on the variation of plasma current $I_p$ and line averaged plasma density $\langle n(t) \rangle$.

**Results**

The registration of Alfvén wave resonances by microwave reflectometry was studied in the typical experimental conditions of the tokamak TCABR. Because of the low frequency band of the reflectometer $16$-$25.5$ GHz the initial rather low value of the line averaged plasma density $\langle n \rangle \approx (0.9-1.2) \times 10^{19}$ m$^{-3}$ was chosen. The typical traces of the plasma parameters are shown in Fig.2. The time window, in which the AW was excited, is shown in Fig.2(b).

In the course of the reflectometer frequency sweeping the amplitude of the diode signal is increased when the microwave cutoff zone coincides with AW resonance zone. In this case the continuous sweeping of the AW resonance zone will result in the repetitive increases of the diode signal for well defined reflectometer frequencies, which can change with the plasma parameters. In the following data analysis the frequency modulating signal was transformed in the frequency-time plane and the contour lines of the amplitude of the diode signal were plotted in Fig.3. It is seen that maximum repetitive increases of the reflectometer signal occur at the frequencies $f \approx 20$-$20.5$ GHz. They correspond to increase of density oscillations induced by AW absorption near the resonant surface, which can be identified as $M=1$, $N=-2$ resonant surface.

**Conclusions**

Low frequency range of the reflectometer $f=16$-$26.5$ GHz gives the possibility to study AW power deposition only at the plasma periphery in the low density regimes of the TCABR tokamak;
Experiments have shown that intensive density oscillations at the AW frequency are detected by the reflectometer close to the plasma boundary.

Selective excitation of the monochromatic AW with definite $M, N$ and the utilization of the more wide range reflectometer is necessary for the implementation of this method for the plasma diagnostics.

Fig. 3 a) Contour plot of the AW signal from the reflectometer as function of the discharge time and of the reflectometer frequency.

b) line averaged plasma density $\langle n_e \rangle$

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References