Registration of Alfvén resonances in TCABR tokamak by the scanning reflectometer at sideband frequencies

L. F. Ruchko,[1,a)] A. G. Elfimov,[1] C. M. Teixeira,[1] J. I. Elizondo,[1] E. Sanada,[1] R. M. O. Galvão,[2] M. E. Manso,[3] and A. Silva[3]
[1]*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
[2]*CBPF, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[3]*Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear - Laboratório Associado, Instituto Superior Técnico, Lisboa, Portugal*

(Received 12 March 2010; accepted 22 December 2010; published online 22 February 2011)

A frequency scanning O-mode reflectometer was used for studies of plasma density oscillations during local Alfvén wave (LAW) excitation in the Tokamak Chauffage Alfvén Brésilien (TCABR) at the frequency $f_A = 5$ MHz. It was found that the spectrum of the reflectometer output signal, which consists mainly of the "beat" frequency f_B, is modified by the LAW excitation, and two additional frequency peaks appear, which are symmetrical in relation to the LAW excitation frequency $f = f_A \pm f_B$. This result opens the possibility to improve the efficiency of studying the LAW induced density oscillations. The symmetry of these frequency peaks yields the possibility of finding the microwave frequency at which the reflectometer cutoff layer coincides with radial position of the LAW resonance zone in the TCABR tokamak. © *2011 American Institute of Physics*. [doi:10.1063/1.3541756]

I. INTRODUCTION

Microwave reflectometry is widely used for measurements of the plasma density profiles[1] and fluctuations[2] in fusion plasmas. Usually these two tasks are separated, the frequency scanning reflectometers are used for plasma density radial profile reconstruction, and the plasma density oscillations are measured at fixed frequencies. The registration of the density oscillations, which are excited by LAW in the TCABR tokamak, by the reflectometer at fixed frequency, was presented in Ref. 3. In this paper, we present experimental results showing that the frequency scanning reflectometry is effective for the registration of the LAW induced density oscillations, and that it offers some advantages for their identification. It is shown that in this case the reflectometer starts to register the density oscillations not at the LAW frequency, ω_A, but at the "sideband" frequencies, $\omega_S = |\omega_A \pm \omega_B|$, where ω_B is the fringe frequency resulting from the beating between the reference and plasma signals.[1]

When the frequency of the reflectometer ω is scanned, the radial position of the reflection zone moves, and when this reflection zone crosses the LAW resonance position r_A, the phase of the reflected microwave signal is modulated by the LAW induced density oscillations. This position, $r = r_A$, depends on the rf frequency ω_A, on the excited wave mode numbers M, N, and on the plasma parameters. Detailed description of the physical phenomena, which constitute the base of registration of the LAW resonances for diagnostics, can be found in Ref. 4. For O-mode reflectometer, the phase of reflected microwave signal after propagation through the plasma to the cutoff layer and back can be found[1] from the equation

$$\varphi(\omega) = \frac{2\omega}{c}\int_{r_c}^{a}\sqrt{1-\frac{n_e(r)}{n_c}}dr - \pi/2. \tag{1}$$

Here n_c is the cutoff plasma density:

$$n_c = \epsilon_0 m_e \omega^2/e^2. \tag{2}$$

The reflection position r_c is determined by the equation $n_e(r_c) = n_c$.The reflected microwave signal, which can be expressed as $A\sin[\omega t + \varphi(\omega) + \varphi_m(\omega)]$, is mixed inside the reflectometer with the reference signal $B\sin[\omega t + \varphi_{\rm ref}(\omega)]$, and the output reflectometer signal can be expressed as

$$\widetilde{U} \sim AB\sin[\varphi(\omega) + \varphi_m(\omega) - \varphi_{\rm ref}(\omega)]. \tag{3}$$

Here $\varphi_m(\omega)$ and $\varphi_{\rm ref}(\omega)$ are the phase shifts, which are introduced by the time delay of the main and the reference signals. In the case of the frequency sweeping $\omega = \omega(t)$, this beat signal is usually used to obtain the profile of plasma density. The fringe frequency of this signal ω_B, which can be introduced through equation $\omega_B t = \varphi(\omega) + \varphi_m(\omega) - \varphi_{\rm ref}(\omega)$, depends on the rate of microwave frequency sweeping $d\omega/dt$, and for the TCABR reflectometer can reach the frequency $f = \omega_B/(2\pi) \approx 10 - 12$ MHz for scanning time $t_S = 8\ \mu$s.

When the reflection position r_c approaches the region where LAW density oscillations $\widetilde{n}(r)$ are excited, this position starts to oscillate with the magnitude $\Delta\widetilde{r}_c \sim \widetilde{n}\,(dr/dn)$ at LAW frequency ω_A, and the phase of reflected microwave signal oscillates accordingly $\Delta\varphi \approx 2\omega/cL_n\,(\widetilde{n}/n)$. Here $L_n = n dr/dn$ is the scale length of the density. In the case of small density perturbations $\Delta\widetilde{r}_c/r_c \ll 1$, we can expand Eq. (3) in the vicinity of r_c and obtain the simplified expression for the output signal of the reflectometer, which consists of the oscillations at the main fringe frequency ω_B and of the

a)Electronic mail: lruchko@if.usp.br.

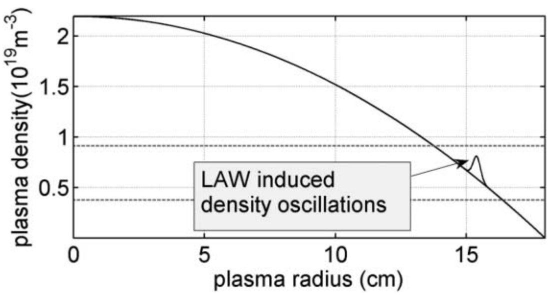

FIG. 1. Plasma density radial profile,which was used in the numerical simulations. The amplitude of the density perturbations was multiplied by 100 for better visibility. The scanned plasma density range $n_e = (0.38 - 0.91) \times 10^{19}$ m^{-3} is shown by dashed horizontal lines.

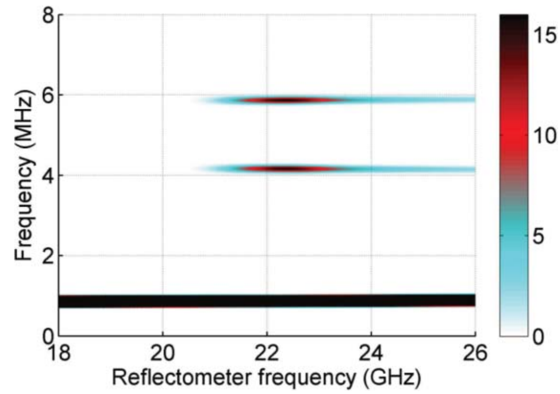

FIG. 2. (Color online) Spectrogram of the signal, which was obtained after numerical simulation of the reflectometer output signal. The magnitude of the power spectral density is plotted.

oscillations at the sideband frequencies $\omega_S = |\omega_B \pm \omega_A|$, here $\alpha \ll 1$:

$$\widetilde{U} \sim \sin(\omega_B t + \varphi_0) + \alpha \sin(|\omega_B \pm \omega_A| t)\,. \qquad (4)$$

This simplified description of the reflectometer phase response to the density fluctuations is true when the change in phase depends primarily on changes in the location of the cutoff layer. The sideband signals can be also produced by the density fluctuations, which are localized away from the cutoff layer.[5] In this case, the phase response of the reflectometer to the oscillating density perturbations may be enhanced due to the Bragg scattering.

The analysis of the dependence of the reflectometer phase response on the density perturbation shape and size can be found in Refs. 6–8. When applying it to the experimental data of the TCABR tokamak, we can find that the LAW driven phase modulation occurs mainly due to the oscillation of the cutoff layer. It is the result of the large scale LAW oscillations, whose typical radial structure is shown in Ref. 4. It can be found that for this case $k_f < 2k_A$, where $k_A = 0.63 k_0^{2/3} L_n^{-1/3} \approx 1$ is the Airy wave number, thus the Bragg condition is not satisfied anywhere along the microwave path, and the dominant contribution to the reflectometer phase response is due to the oscillation of the cutoff layer.

In order to confirm the result of the sidebands frequencies generation, numerical simulations were performed for parabolic plasma density profile, which is shown in Fig. 1. The model perturbation of the plasma density, which is created by the LAW excitation, is shown. Its magnitude oscillates with the rf frequency $f_A = \omega_A/2\pi = 5$ MHz.

The frequency of the reflectometer was swept linearly in the range $f = 18 - 26$ GHz, during the time $\tau_s = 80\ \mu$s. In the course of the numerical simulations, Eq. (1) was integrated with sampling time interval $\tau_{\mathrm{samp}} = 5$ ns, and the obtained value $\varphi(\omega)$ was substituted in Eq. (3). The parameters $\varphi_m(\omega)$, $\varphi_{\mathrm{ref}}(\omega)$ were chosen in such a way that the fringe frequency ω_B lies in the range $f_B = \omega_B/2\pi = (0.9 - 1.1)$ MHz, which is close to the real parameters of the reflectometer.

The spectrogram of $\widetilde{U}$, which simulates the output signal of the reflectometer, is shown in Fig. 2. It is seen that when, in the course of the frequency increasing, the position of the cutoff zone approaches the region with LAW induced density oscillations, the reflectometer registers the occurrence of the signals at the frequencies $f = (5 \pm 1)$ MHz. This result can be explained by the appearance of the sideband frequencies $\omega_S = |\omega_A \pm \omega_B|$ in accordance with Eq. (4). It is clearly seen that when the reflection position r_c reaches the LAW zone, the fringe frequency starts to be accompanied by the sideband harmonics. As it is shown in Ref. 2, the reflectometry signals are extremely sensitive to plasma density oscillations in the cutoff zone. Therefore, the amplitude of the signal at sideband frequencies decreases when the reflectometer frequency increases further, and the position of the reflection zone leaves the zone of LAW induced density oscillations. The Fig. 2 spectrogram shows that the amplitude of these sideband harmonics has maximum in the vicinity of the LAW induced density oscillations, and it means that the position of the LAW zone can be accurately found.

II. EXPERIMENTAL SETUP

The experiments were carried out in the tokamak TCABR ($a = 0.18$ m, $R = 0.61$ m, $B = 1.1$ T). The basic parameters in this investigation were: plasma current $Ip = 70 - 95$ kA, edge safety factor $q(a) \simeq 3.1 - 4$, line averaged plasma density $\overline{n}_e = (0.9 - 1.5) \times 10^{19}$m^{-3}, working gas was hydrogen. In the basic regime of operation LAW was excited by two antenna modules, which are toroidally separated by angle $\theta = \pi$. The rf power absorbed by the plasma was limited to $\widetilde{P}_a \leq 40$ kW and the frequency was fixed at $f_A = \omega_A/2\pi = 5.0$ MHz. The straps in the same toroidal cross sections are fed by rf currents with $(0, \pi)$ phasing so that they can excite mainly the modes $M = \pm 1$, $N = \pm 1, \pm 2$. Here M and N are poloidal and toroidal wave numbers, respectively.

The microwave reflectometer was constructed in Instituto de Plasmas e Fusão Nuclear (IPFN), Lisbon. It can operate in two bands (K and Ka) and is capable to successive fast ($\tau \geq 8\mu$ s) frequency sweeps from 18 to 40 GHz in the course of plasma discharge. It incorporates the advanced telecom computing architecture crate with Intel Core 2 Duo central processing unit. The system has four data acquisition channels with 13 bits resolution and 2 Gbytes of shared on board memory. The master board also communicates with the ramp generator via an RS232 connection and can set the pa-

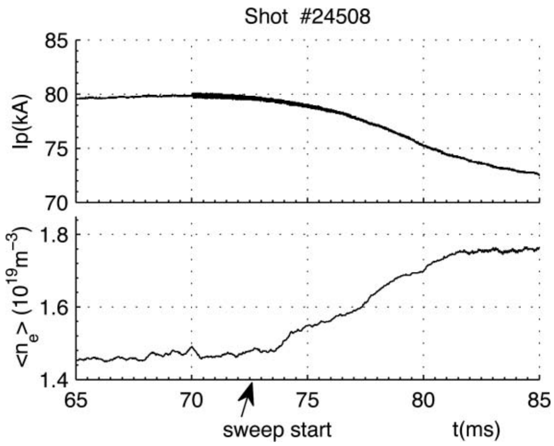

FIG. 3. Shot #24508. Traces of the plasma current (top) and line averaged plasma density (bottom).

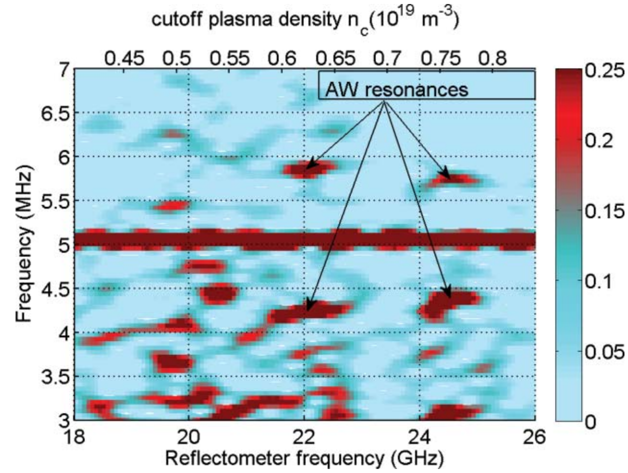

FIG. 4. (Color online) Shot #24508. Spectrogram of the reflectometer signal during AW excitation at time $t = 72.6$ ms. The magnitude of the power spectral density is plotted. The scanning frequency is shown at the bottom x axis, and the corresponding cutoff plasma density is shown at the top.

rameters for the operation of the reflectometer (sweep time, trigger mode, frequency range, fixed frequency values, etc). In these experiments, the duration of the frequency sweeping was set to $t_S = 80\ \mu$s, and the K band was used. The sampling frequency of the reflectometer data acquisition system was 200 MHz. The antennae of the reflectometer were installed inside the vacuum chamber in the tokamak midplane in the immediate vicinity of the plasma.

III. RESULTS

The registration of LAW resonances by frequency sweeping microwave reflectometry was studied in the typical experimental conditions of the tokamak TCABR. The reflectometer was switched on at the initial phase of the tokamak discharge, and it continued to make successive frequency scans until the plasma decayed. The rf generator, which powered the Alfvén wave (AW) antennae, was switched on at the moment, when the plasma current I_p reached the quasistationary phase. The duration of the rf pulse was varied in the range $\tau = 5 - 10$ ms. The rf power deposition was accompanied by some plasma density increase, and LAW resonances with wave numbers $M = \pm 1$, $N = \pm 1, \pm 2$ were excited inside the plasma column.

The TCABR shot #24508 was used for the analysis, the traces of the plasma current Ip and line averaged plasma density are shown in Fig. 3. The rf generator was turned on at time $t = 70$ ms, rf pulse duration was $t_A = 7$ ms. In order to improve the frequency resolution of LAW resonances ($f_A = 5$ MHz), the reflectometer scanning time was set to $t_S = 80\ \mu$s, the fringe frequency in this case was $f = 0.8$–1.2 MHz.

The spectrogram of the output reflectometer signal, which was obtained in the course of the LAW excitation, is shown in Fig. 4. At first we can see the strong signal at the frequency $f = 5$ MHz. It is parasitic pick-up of the rf signal. It is shortcoming of the diagnostic equipment, but in our case it does not prevent the data analysis, and it can be used as a reference signal. More interesting are the signals, which are symmetric in relation to this reference signal. As it was discussed above, these signals can represent the sideband harmonics $\omega_S = |\omega_A \pm \omega_B|$, which appeared due to LAW driven density oscillations , as it is given by the Eq. (4). That is, in order to find out the reflectometer frequencies, which correspond to reflection from the AW zone, it is sufficient to sort out the signals with approximately the same amplitude and which are symmetric in relation to the reference signal. As example, for spectrogram, which is shown in Fig. 4, the reflectometer frequencies, corresponding these requirements, are equal to $f_1 \approx 22$ GHz and $f_2 \approx$24.5 GHz. A more detailed analysis of the experimental data reveals also the sideband signals that are produced due to the passing of the microwave signal, which has cutoff zone outside the LAW zone, through the LAW resonance layer.[5] These signals can be seen as weak traces in the numerical simulation in Fig. 2; however, because of their small magnitude, they fall below the level of the background density fluctuations for our experimental conditions and can not be distinguished in Fig. 4.

It has to be noted here that experimentally measured "beat" frequency ω_B depends on the wave guide dispersion, and for our reflectometer it decreases with its frequency. And indeed we can see in Fig. 4 that sideband harmonics at $f_2 \approx 24.5$ GHz are closer to the reference signal than at $f_1 \approx 22$ GHz. These data agree with the results of the experiments on LAW resonances identification, which were made in the TCABR earlier.[4] The sidebands seen at the reflectometer frequency f_1 ($n_c = 0.6 \times 10^{19}\mathrm{m}^{-3}$) are due to LAW resonance $M/N = 0/2$, and the sidebands at frequency f_2 ($n_c = 0.75 \times 10^{19}\mathrm{m}^{-3}$) may be attributed to LAW resonance $M/N = \pm 1/\pm 2$.

IV. CONCLUSION

The experiments have shown that frequency sweeping reflectometry is efficient diagnostic technique for registration of density oscillations, which are induced by LAW resonances in tokamaks. The possibility to use the registration of oscillations at sideband frequencies, which are symmetrical in relation to driving LAW frequency, improves discrimination of the density oscillations at the LAW frequency significantly. The advantage of this diagnostic technique is the possibility not only to register the occurrence of the LAW driven density oscillations, but also the possibility to find their radial position by the reconstruction of the density profile at the same instance. It may be a very efficient diagnostic tool for localization of the LAW resonances in order to find the effective mass number M_{eff} and $q(r)$ profiles in tokamaks.

ACKNOWLEDGMENTS

This work has been supported by the National Council for Scientific and Technological Development CNPq and the State of Sao Paulo Research Foundation FAPESP.

[1] C. Laviron, A. J. H. Donné, M. E. Manso, and J. Sanchez, Plasma Phys. Controlled Fusion **38**, 905 (1996).
[2] R. Nazikian, G. J. Kramer, and E. Valeo. Phys. Plasmas **8**, 1840 (2001).
[3] L. F. Ruchko, R. Valencia, R. M. O. Galvão, E. A. Lerche, A. G. Elfimov, V. Bellintani, Jr., J. I. Elizondo, A. N. Fagundes, A. M. M. Fonseca, Yu. K. Kuznetsov, I. C. Nascimento, W. P. de Sá, E. Sanada, and R. P. da Silva, Rev. Sci. Instrum. **75**, 655 (2004).
[4] A. G. Elfimov, L. F. Ruchko, R. M. O. Galvão, J. I. Elizondo, E. Sanada, Yu. K. Kuznetsov, A. N. Fagundes, W. P. de Sá, C. A. F. Varandas, M. E. C. Manso, P. Varela, A. Silva, and A. A. Ivanov, Nucl. Fusion **46**, S722 (2006).
[5] M. A. Heald and C. B. Wharton, *Plasma Diagnostics with Microwaves* (Wiley, New York, 1965), Chap. VI, Sec. 6.6, p. 229.
[6] N. Bretz, Phys. Fluids B **4**, 2414 (1992).
[7] B. B. Afeyan, A. E. Chou, and B. I. Cohen, Plasma Phys. Controlled Fusion **37**, 315 (1995).
[8] C. Fanack, I. Boucher, F. Clairet, S. Heuraux, G. Leclert, and X. L. Zou, Plasma Phys. Controlled Fusion **38**, 1915 (1996).