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Determination of Rational Surface Position and Magnetic Island Width From Electron Cyclotron Emission (ECE) Radiometry in TCABR

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***Abstract*—Measurements of the electron temperature radial profile $T_e(r)$ have been performed on the Tokamak Chauffage Alfvén Brésilien tokamak with high radial resolution, using an electron cyclotron emission radiometer. The temperature profile shows distinct peculiarities in discrete radial regions which can be associated with the presence of magnetic islands. A method is proposed here to determine the radial positions and widths of the magnetic islands based upon measurement of the Fitzpatrick kind, not completely flattened, radial profile of the electron temperature $T_e(r)$. In combination with other well-known methods, the suggested methods can give additional possibilities for comparing experimental and theoretical results in the study of magnetic islands.**

***Index Terms*—Island width, magnetic island, radiometry, temperature profile, Tokamak.**

I. INTRODUCTION

THE STUDY of magnetic structures inside the plasma is one of the most important subjects in the investigation of stability and transport properties in tokamaks. Therefore, many experiments have been carried out to extract information about thermal and particle transport coefficients, or about internal magnetic structures, using different methods and diagnostics, as pellet injection [1], [2], heat pulse wave propagation [3]–[5], or neutral beam injection [6], [7]. However, these experimental approaches demand the construction and operation of sophisticated systems and a comprehensible analysis of the results must be carried out with care since the interpretation of the involved physical phenomena is not straightforward. Alternatively, useful information on internal magnetic structures can be extracted from electron temperature fluctuations. They can originate from the heat propagation after an internal disruptions, such a sawtooth collapse, or from variations of the heat transport across the magnetic islands, due to the competition between anomalous perpendicular heat conduction and other transport mechanisms, resulting in not completely flattened electron temperature radial profile $T_e(r)$.

One effective diagnostic often used in these studies has been electron cyclotron emission (ECE) radiometry (see [8]–[10]). In this work the results obtained with this type of diagnostic on the Tokamak Chauffage Alfvén Brésilien (TCABR) tokamak are presented and discussed. Typically, measurements of the electron temperature with high radial and temporal resolutions show peculiarities in the radial profiles of $T_e(r)$, which are usually associated with rational magnetic surfaces, $q(r) = m/n$, where $q(r)$ is the safety factor and (m, n) are the poloidal and the toroidal mode numbers, respectively. In the TCABR discharges with $q(a) \simeq 3.5$ (a is the tokamak minor radius), the temperature and its perturbation profiles exhibit reproducible peculiarities related to the magnetic islands near the rational magnetic surfaces (1,1), (4,3), (3,2), and (2,1). Here we are mainly interested in the magnetic islands with $q(r_s) = 2$, or with $(m, n) = (2, 1)$, where r_s is the radius of the rational magnetic surface. In the vicinity of these rational surfaces, the temperature fluctuations are dominated by the well-known effect caused by the Fitzpatrick type of not completely flattened radial profile of the electron temperature [11]–[13]. In this paper we propose a novel and effective method of determining the locations and widths of magnetic islands in tokamak plasmas, using only measurements of the T_e fluctuations originating from the mentioned mechanism.

The sweeping ECE radiometer used in our measurements is described in Section II. The experimental conditions are also discussed in this section. In Section III, the results the experimental measurements are presented and discussed. In Section IV, a new method for determining of the position of the rational surface and widths of magnetic islands by ECE radiometry is discussed. The conclusion of this work is presented in Section V.

II. EXPERIMENTAL SETUP AND EXPERIMENTAL RESULTS

Electron temperature profiles are routinely measured in the TCABR tokamak (major radius $R_0 = 0.615$ m, minor plasma radius $a = 0.18$ m, toroidal magnetic field $B_0 \approx 1.1$ T, and plasma current $I_p \leq 110$ kA) with a sweeping ECE radiometer (50–85 GHz, second-third ECE harmonics, extraordinary mode). The intermediate 2-GHz frequency bandwidth determines a radial resolution of about 2 cm at the center of the plasma column, and, consequently, causes a smoothing in the temperature profile. The radiometer is used in the sweeping mode of operation with stepwise changes in frequency. The time resolution is limited by a 40-μs time lag, required for

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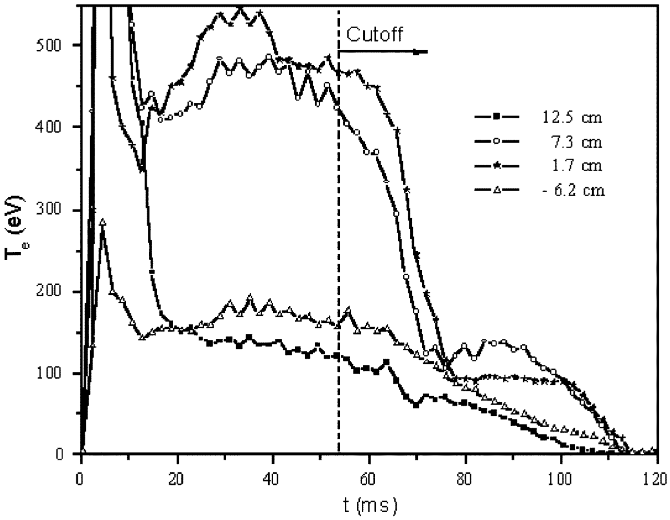

Fig. 1. Temporal profiles obtained for the radial positions 12.5 cm, 7.3 cm, 1.7 cm, and -6.2 cm.

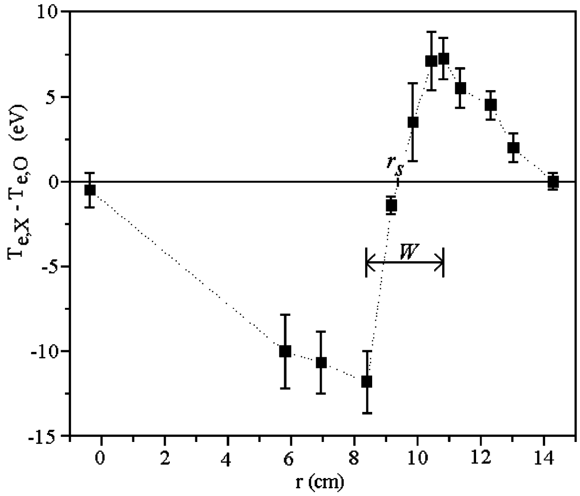

Fig. 2. Amplitude of the MHD oscillations obtained from the difference between the electron temperature when the X and O points pass in the front of the antenna. Data were averaged over 3–4 cycles of MHD oscillations, measured for each radial position. Magnetic island width $W \sim 2.4$ cm and the rational surface localized at $r_s \sim 9$ cm, are shown.

stabilizing the local oscillator, after a frequency change. Therefore, there is a trade off between space and time resolutions. For good space resolution, 20–60 frequency steps are required, so that the time interval between measurements at the same radial position can vary between 0.8–2.4 ms. An alternative is to obtain radial profiles from reproducible discharges, on a shot-by-shot basis, using a fixed radiometer frequency for each shot with a high time resolution (10 μs). In this case, the temperature fluctuations can be fully characterized at a fixed radial position and its average radial properties can be determined from comparing the behavior of similar reproducible discharges.

Since the TCABR tokamak is a small machine with low toroidal magnetic field, accessibility and absorbability conditions of the ECE measurements are rather restricted, i.e., only a narrow interval of line average densities, approximately from $1.0 \times 10^{19}\ \mathrm{m}^{-3}$ to $1.5 \times 10^{19}\ \mathrm{m}^{-3}$, allows full temperature profile measurements. In addition to the nonthermal emission effects [14] caused by suprathermal electrons in the low-density limit and the cutoff of the plasma emission [15], [16] in high density limit, it is necessary to take into account the blackbody condition in terms of the optical depth, which does not allow accurate T_e measurements near the plasma boundary.

An example of measurements in which these restrictions are exemplified, is given in Fig. 1. The strong emission at the startup phase of the discharge is caused by the presence of suprathermal (runaway) electrons, due to the low plasma density and high toroidal electric field conditions [17]. Afterwards, with the increase of density and decrease of the electric field, this effect disappears. At the flattop phase of the discharge, the cutoff effect is observed in the ECE signals for $t > 55$ ms, when the line average density increases above $1.5 \times 10^{19}\ \mathrm{m}^{-3}$.

A detailed description of the experiments to measure the T_e radial profiles and determine the influence of the magnetohydronamic (MHD) oscillations on their temporal evolution, with the ECE radiometer operating in the sweeping mode, can be found in [18]. Here, we review only the main points of those experiments. Similar electron temperature oscillations were found in Tokamak Experiment for Technology Oriented Research (TEXTOR) [19], [20], JT-60U (Japan Atomic Energy Research Institute Tokamak-60 Upgrade) [21], and JFT-2M (Japan Atomic Energy Research Institute Fusion Torus-2M) [22]. However, a detailed analysis of the experimental results is not presented in these publications.

The amplitude of the MHD oscillations observed in the T_e radial profile, due to the variation of the electron temperature when the X and O points pass in the front of the antenna, is shown on Fig. 2. In the sequel, we present the method to determine the island width from these data, based upon the Fitzpatrick theoretical model of competing mechanisms for heat conduction across a magnetic island.

III. FITZPATRICK TYPE OF NOT COMPLETELY FLATTENED RADIAL PROFILE OF THE ELECTRON TEMPERATURE

Let us consider a situation with central $q(0) > 1$, so that disruptions are absent, and such that the conditions for the application of the Fitzpatrick model are verified [11]. It is sufficient for us to use the simplified version of the theory developed in [11], although later more complicated analytical models were elaborated (see, e.g., [13] and references therein). In this theory, the electron heat diffusion equation is used in the form [11]

$$\boldsymbol{\nabla} \cdot \mathbf{q}_e = 0. \tag{1}$$

Here, $\mathbf{q}_e$ is the electron heat flux given by

$$\mathbf{q}_e = -n_0 \left(\chi_{||} \mathbf{b} \nabla_{||} + \chi_{\perp} \boldsymbol{\nabla}_{\perp}\right) T_e, \tag{2}$$

n_0 is the plasma number density, T_e is the electron temperature, $\chi_{||}$ and $\chi_{\perp}$ are the parallel and perpendicular heat conductivity coefficients, respectively, $\nabla_{||} = \mathbf{b} \cdot \boldsymbol{\nabla}$ and $\boldsymbol{\nabla}_{\perp} = \boldsymbol{\nabla} - \mathbf{b}\nabla_{||}$ are the parallel and perpendicular gradients (with respect to the total magnetic field $\mathbf{B}$), and $\mathbf{b} = \mathbf{B}/B$ is the unit vector along $\mathbf{B}$. The parallel heat flux $\mathbf{q}_{e||}$ is assumed to be collisional or convective, and the perpendicular heat flux, $\mathbf{q}_{e\perp}$, anomalous.

The radial profile of the electron temperature sets in as a result of competition between the parallel and perpendicular heat fluxes. Details of the solution of (1) can be found in [11]–[13] and [18]. We are only interested in the main results. We assume that the island chain is localized in the vicinity of an equilibrium rational (singular) magnetic surface $r = r_s$ (r is the radial coordinate) and introduce the radial deviation from the rational magnetic surface $x = r - r_s$. The electron temperature in the vicinity of the magnetic island is represented in the form

$$T_e = T_0(r) + T_c(x)\cos\xi \tag{3}$$

where $T_0(r)$ and $T_c(x)$ are the equilibrium and perturbed temperature profiles, respectively, and the function ξ is the island cyclic variable

$$\xi = m\theta - n\zeta - \omega t. \tag{4}$$

Here, m and n are the poloidal and toroidal mode numbers and θ and ζ are the poloidal and toroidal angles, respectively.

To choose the electron parallel heat conductivity, $\chi_{\|}$, collisional or convective, we should compare the electron mean-free-path $\lambda_e \simeq (T_e/M_e)^{1/2}/\nu_e$ with the characteristic length of the helical perturbations in the magnetic island $\lambda_{\|} = 1/k_{\|}$, where [11]

$$k_{\|} = \frac{-k_y W}{L_s} \tag{5}$$

$k_y = m/r$, W is the island width, $L_s = qR/s$ is the shear length, $s = r_s q'/q$, q is the safety factor, and prime "$'$" denotes radial derivative. The parameter $\lambda_e/\lambda_{\|}$ in the TCABR tokamak is not too large, $\lambda_e/\lambda_{\|} \simeq 5.8 \div 3.3$ [18]. This means that, although the collisional model, with the parallel heat conductivity in the Braginskii form, is more acceptable, the convective model cannot be excluded from consideration.

For the collisional model, the solution $T_c(x)$ can be constructed in the form [11], [18]

$$T_c(x) = -\frac{7W^2 T_0'}{80}\frac{x}{x^2 + \frac{\sqrt{2\pi}W_{\rm col}^2}{8\Gamma^2\left(\frac{3}{4}\right)}} \tag{6}$$

where $W_{\rm col}$ is the characteristic island width defined by

$$W_{\rm col} = 2^{3/2}\left(\frac{L_s^2\chi_\perp}{k_y^2\chi_{\|}}\right)^{1/4} \tag{7}$$

and $\Gamma(3/4)$ is the Euler gamma-function of the argument $3/4$. As follows from (6), a maximum value of the function $T_c(x)$ is reached at $x_{\max} = W_{\rm col}/2$, [11], [18]

$$T_c\left(x_{\max}\right) = \frac{-1.44W^2 T_0'}{16W_{\rm col}}. \tag{8}$$

When the electron heat conductivity, $\chi_{\|}$, is not collisional but convective, the electron temperature profiles in the magnetic island region can be represented in the form [11], [18]

$$T_c(x) = -\frac{W^2 T_0'}{16}\frac{x}{x^2 + \frac{12^{1/3}W_{\rm conv}^2}{16\Gamma\left(\frac{2}{3}\right)}} \tag{9}$$

where $W_{\rm conv}$ is the characteristic island width for the convective mechanism of the parallel transport, defined by

$$W_{\rm conv} = \left(\frac{2^{11/2}\chi_\perp L_s}{c_s k_y}\right)^{1/3} \tag{10}$$

and $c_s = [5T_0/(3M_e)]^{1/2}$ is the generalized "sound" speed for electrons [13] with $x_{\max} = W_{\rm conv}/3.1$, and

$$T_c(x_{\max}) = \frac{-1.55W^2 T_0'}{16W_{\rm conv}}. \tag{11}$$

However, to make this result consistent with [11], an uncertainty factor $k \sim 1.5$ has to be introduced here.

IV. DETERMINATION OF THE RATIONAL SURFACE POSITION AND MAGNETIC ISLAND WIDTH

As was mentioned in Introduction, there are many methodics to extract information about internal magnetic structures; for example, pellet injection [1], [2], heat pulse wave propagation [3]–[5], or neutral beam injection [6], [7]. The mostly widespread method to calculate the magnetic island width is to use the equation

$$W = 4\sqrt{\frac{r_s B_r(r_s) q(r_s)}{m B_\theta(r_s) q'(r_s)}} \tag{12}$$

where $B_r\,(r_s)$ is the radial component of the perturbed magnetic field on the rational surface obtained from measurements by Mirnov coils using the well-known expression

$$B_r(r_s) = B_r(r_c)\left(\frac{r_c}{r_s}\right)^{m+1}. \tag{13}$$

Here, $B_r(r_c)$ is the radial component of the perturbed magnetic field on the Mirnov coils and r_c is the radial localization of these coils.

The size of the magnetic island can be also estimated using [19]

$$W \approx \frac{2T_c(x_{\max})}{|\nabla T_e|} \tag{14}$$

where ∇T_e is the gradient of temperature between the measurements where the temperature perturbation maximum occurs and where the perturbation reverses sign.

It is clear that our experimental results, Fig. 2, and (8) and (11) gives us a possibility to use a new method to calculate the magnetic island width, as follows. For the collisional model, we find from (8) the expression for the magnetic island width

$$W = \left[\frac{-11.1 W_{\mathrm{col}} T_c\left(x_{\max}\right)}{T_0'}\right]^{1/2}. \tag{15}$$

The value W_{col} is calculated from (7) using experimental results and the expression for the perpendicular heat conductivity coefficient $\chi_\perp$

$$\chi_\perp \sim \frac{a^2}{6\tau_E} \tag{16}$$

where a is the plasma radius and τ_E is the plasma energy confinement time for ohmically heated plasmas [24]

$$\tau_E\left(s\right) = 0.07\left(\frac{n\mathrm{m}^3}{10^{20}}\right) aR^2 q. \tag{17}$$

The value $T_c(x_{\max})$ is found from the Fig. 2. It is clear also that we can estimate the radial location of the separatrix as the middle of the distance between maximum and minimum of the temperature in Fig. 2.

For the convective model, we find analogously from (11)

$$W = \left[\frac{-10.3 W_{\mathrm{conv}} T_c(x_{\max})}{T_0'}\right]^{1/2} \tag{18}$$

where W_{conv} can be found from (10) using experimental results and $T_c(x_{\max})$ from the corresponding experimental results presented in a figure analogous to Fig. 2.

Let us summarize data on magnetic island width. The paper pres

1) From measured magnetic fields [note any inward extrapolation, if coils are not at the resonant surface, is nontrivial (see [25])]. Analysis of experimental data shows that the magnetic island width W in our case is (see [18])

$$W \simeq 1.5 \div 2.5 \text{ cm}. \tag{19}$$

This result was obtained using (12).

2) From the width between the two perturbed temperature peaks (we remind that, according to [26], there is a subtlety that only the fundamental should be used). From Fig. 2, we find that the magnetic island width W is

$$W \simeq 2.4\,\mathrm{cm}. \tag{20}$$

3) From a collisional model, using (15), we get

$$W \simeq 1.6 \div 1.7\,\mathrm{cm}. \tag{21}$$

4) From a convective model, substituting the macroscopic parameters of the TCABR tokamak into (18), we obtain

$$W \simeq 2.1 \div 2.2\,\mathrm{cm}. \tag{22}$$

For these calculations, we use the equilibrium radial profile of the electron temperature $T_0(r)$

$$T_0(r) = T_e\left(0\right)\left(1 - \frac{r^2}{a^2}\right)^l \tag{23}$$

with $1.5 \leqslant l \leqslant 2.5$ [18]. We see from (20)–(22) that these estimations of the magnetic island width are inside the interval of (19) obtained by magnetic measurements.

V. CONCLUSION

Electron temperature measurements by ECE diagnostics have been carried out in the TCABR tokamak with high radial and temporal resolutions. In this work, we show that the measured radial profiles of the temperature and its fluctuations show interesting peculiarities, which are related to the presence of magnetic islands. Therefore, the T_e perturbation measurements using an ECE diagnostic system, with appropriate radial and temporal resolution, are suggested here as a useful tool for evaluating the position and the width of magnetic islands, and, consequently, the plasma density current profile. In combination with other well-known methods, the suggested methods can give additional possibilities for comparing experimental and theoretical results in the study of magnetic islands.

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