Report on recent results obtained in TCABR

2015 J. Phys.: Conf. Ser. 591 012001

(http://iopscience.iop.org/1742-6596/591/1/012001)

15th Latin American Workshop on Plasma Physics (LAWPP2014) IOP Publishing
Journal of Physics: Conference Series **591** (2015) 012001 doi:10.1088/1742-6596/591/1/012001

Report on recent results obtained in TCABR

RMO Galvão[1], CHS Amador[2],WAH Baquero[1], F Borges[3], IL Caldas[1], NAM Cuevas[1], VN Duarte[1], AG Elfimov[1], JI Elizondo[1], AMM Fonseca[1], TM Germano[1], GG Grenfell[1] , ZO Guimarães-Filho[1], JL Jeronimo[1], YuK Kuznetsov[1], MAM Manrique[1], IC Nascimento[1], CJA Pires[1], PGP Puglia[1], AP Reis[1], G Ronchi[1], LF Ruchko[1], WP de Sá[1], RJF Sgalla[1], EK Sanada[1], JHF Severo[1], VC Theodoro[1] and D.L. Toufen[4]

[1] Instituto de Física da Universidade de São Paulo, São Paulo, Brasil.
[2] Universidade Tecnológica Federal do Paraná, Cornélio Procópio, Brasil.
[3] Instituto de Física, Universidade Federal Fluminense, Brasil.
[4] Instituto Federal de Educação, Ciência e Tecnologia de São Paulo, Guarulhos, Brasil.

E-mail: rgalvao@if.usp.br

Abstract. Recent results of experimental work and theoretical modeling carried out in the TCABR tokamak are reported on characterization of MHD instabilities, improved diagnostics of rotation of the plasma column, excitation of Alvén global modes, identification of GAMs, and the effect of rotation on their behavior. Detailed measurements of edge electrostatic perturbations and of magnetic island evolution and rotation indicate that the edge turbulence is substantially affected by the islands growth, leading to a strong modulation of the edge particle losses at the same frequency of the MHD activity. Measurements with spatial resolution also show that the growth of the MHD activity is due to nonlinear coupling of magnetic islands with different poloidal mode numbers, which increases the impurity influx. A new system of data acquisition and processing of the TCABR plasma rotation diagnostic was implemented. The system is based upon a single monochromator coupled with six photomultipliers tubes and allows one toroidal and two poloidal simultaneous rotation measurements. The excitation of Global Alfvén Waves - GAW has been investigated, using a new type of radio frequency amplifier. The GAW resonances are searched either by a pre-programmed density variation, at fixed generator frequency, or through three RF frequency sweeps from 2 to 4.5 MHz, at stationary density. GAW resonances have been found and their somewhat new characteristics are presented. The investigation of the effect of poloidal and toroidal rotation on the characteristics of the geodesic acoustic mode has been investigated, both theoretically and experimentally. It is found that the assumption of isothermal flux surfaces gives rise to a third branch of this mode. Detailed predictions coupled with experimental measurements are currently being carried out to investigate this question.

1. Introduction

The TCABR tokamak was designed and built at the *Centre de Recherches en Physique des Plasmas - CRPP*, École Politechnique Fédérale de Lausane, with the main objective of investigating plasma heating by Alfvén waves [1]. It was operated in CRPP from 1980 to 1992, approximately. A couple of years after being de-commissioned, its main components were transferred to the Plasma Physics Laboratory of the University of São Paulo, where the tokamak was rebuilt, with new systems of discharge control and of Alfvén wave excitation, and renamed TCABR, for Tokamak Chauffage Alfvén Bresilien. It started operating in São Paulo in 1999 and produced the first new results around a year later [2,3].

The main parameters of TCABR are major radius R = 0.61m, minor radius a = 0.18m, toroidal magnetic field B = 1.1T, plasma current $I_p \leq$ 100kA, plasma density $n \leq 3\times10^{19}\text{m}^{-3}$, and electron temperature $T_e \leq$ 650 eV. The discharge lasts approximately 100ms, with flat-top plasma current around 40 to 60ms. In this paper we discuss recent results obtained in TCABR on the characterization of MHD activities, measurement of the plasma column rotation, relation between long-range correlations and Geodesic Acoustic Modes - GAMs, and excitation of Global Alfvén Waves – GAWs.

2. Characterization of MHD Instabilities

One of the main lines of research in TCABR, as in many other 'small tokamaks', is the investigation of improved confinement regimes triggered by electrostatic polarization of the plasma edge by external electrodes [4]. Along this line, one of the relevant results obtained in TCABR was on the effect of MHD activity on the triggering and maintenance of the improved confinement regime [5,6].

Although strong MHD activity can entirely suppress improved confinement [6], some conditions have been found in which this regime can survive to somewhat milder activity. An example can be seen in figure 1. In discharge 24126, the polarization pulse has been applied after the occurrence of strong MHD activity and a density rise combined with a little decrease of H-alpha emission is observed, as usual in the TCABR improved confinement regime [5]. The discharge programming was then slightly modified to delay the occurrence of the MHD activity, in order to make it coincide with the application of the polarization pulse, discharge 24128. In this case the MHD activity is not as strong as in cases previously reported [6]. Although only a short decrease in the H-alpha is observed and disappears when the MHD activity sets in, the density remains high during the polarization pulse.

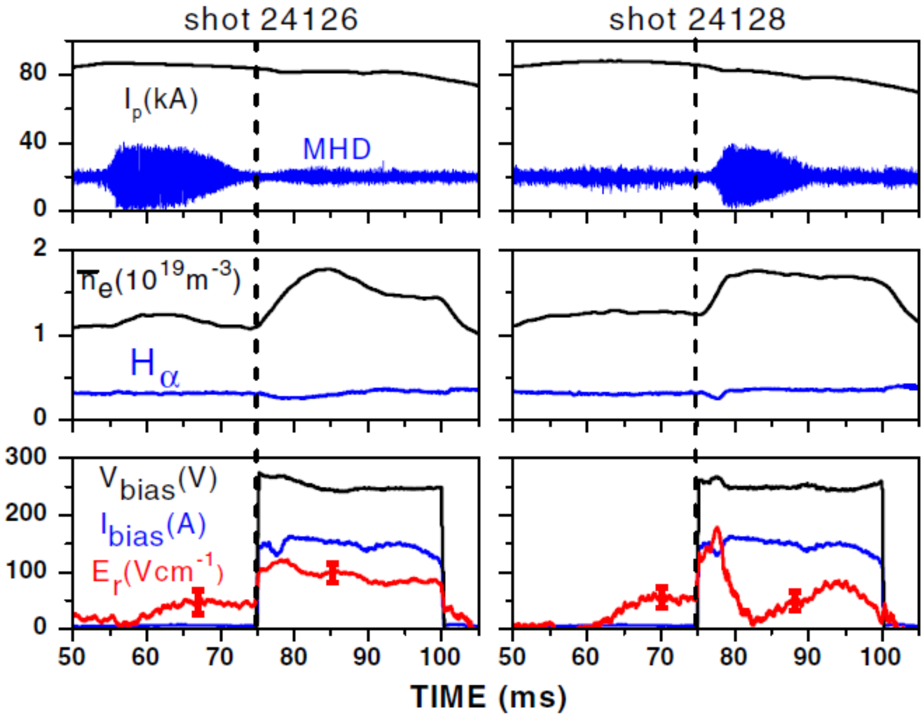


Figure 1 Time traces of plasma current (I_p), Mirnov coil signal (MHD), line average plasma density at the center of the plasma column ($\bar{n}_e$), H-alpha emission, electrode polarization voltage (V_{bias}) and current (I_{bias}), and edge radial electric field (E_r) measured with a radial array of Langmuir probes for discharges 24126 and 24128 of TCABR.

The MHD activity may growth in TCABR up to a saturated stage with large magnetic islands even in the Ohmic phase, as in the case of discharge 24126. For another TCABR discharge with high MHD activity, figure 2 shows the quite similar spectral behavior of the magnetic oscillations and turbulent fluctuations, which indicates that the edge turbulence is modulated by the magnetic islands during the high MHD phase of the discharge. Moreover, figure 2(c) shows that the particle losses are also synchronized with the MHD signals.

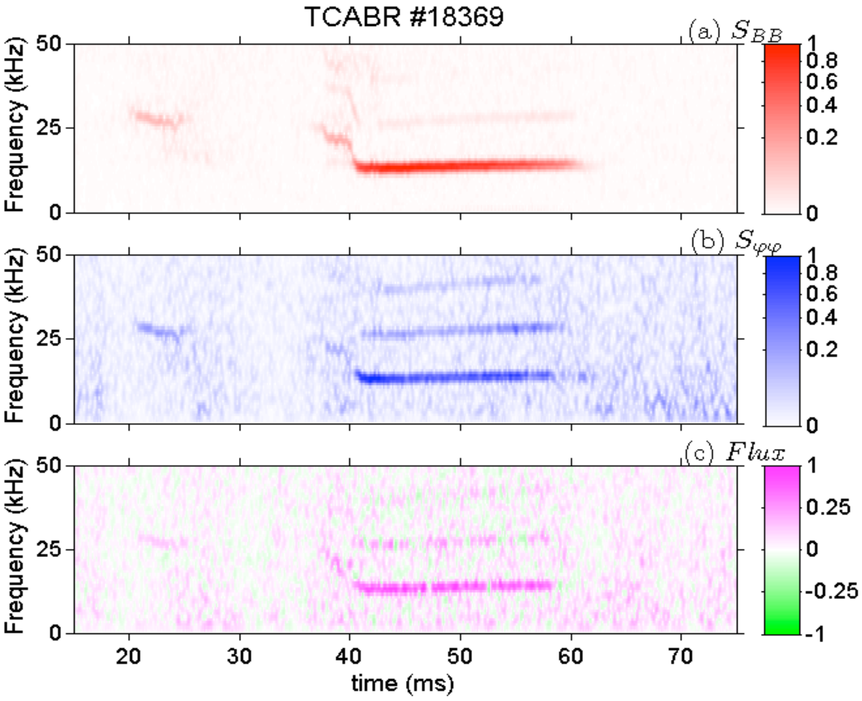
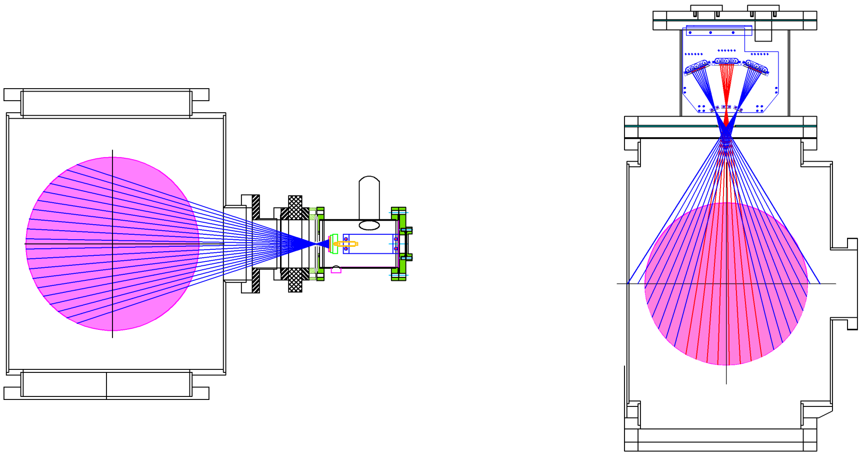


Figure 2 Spectrograms of (a) Mirnov coil signal (MHD), (b) floating potential fluctuations measured with Langmuir probes, and (c) the spectral contribution for the turbulence-driven radial particle flux for discharge 18369 of TCABR.

To better investigate the dynamics of the growth of the MHD activity and their effect on the confinement, we have combined the external magnetic measurements (twenty-four Mirnov coils in a poloidal cross-section closely surrounding the circular plasma column) with soft X-rays and total radiation measurements. The soft X-ray array views the plasma column laterally, from the low-field side, along twenty chords, while the bolometer array views the plasma column vertically, from top to bottom, along twenty-four chords, as shown in figures 3(a) and 3(b), respectively.



(a) (b)

Figure 3 Layout of the soft X-ray (a) and bolometer (b) arrays in TCABR

We have found out that during the growth of the MHD activity a large impurity influx associated with coupling of islands of different mode numbers is often observed. This is illustrated for discharge 26880, shown in figures 4 and 5. In this case, two MHD modes are observed in the spectrogram in the time interval $54 \leq t \leq 69$ ms, approximately. These modes correspond to poloidal mode numbers $m = 2$ ($f \approx 17$ kHz) and $m = 3$ ($f \approx 20$ kHz). At $t \approx 68$ ms, there is a programmed slight increase in the plasma current and the two modes merge, becoming a dominantly $m = 2$ mode with substantially larger intensity and a somewhat smaller frequency, $f \approx 12$ kHz, than before merging.

As the value of the cylindrical safety factor, indicated by the pink trace in the spectrograms for the mode number, is just below four, it is expected that the $m = 3$ is located rather close to the plasma boundary. Therefore, when it couples with the $m = 2$, a larger saturated island is formed [7], bringing in part of the edge plasma and, possibly, impurities. This effect is indeed corroborated by the radial profiles of soft X-ray and bolometer emissions and by a drop in the central electron temperature, as shown in figure 4. When the two modes merge, at $t \approx 68$ ms, there is a large broadening of the emission observed in the central chords of both the X-ray and radiation diagnostics, concurrent with the drop in the central electron temperature measured with ECE. Although in this discharge the mode coupling was triggered on purpose, through the slight increase in the plasma current, it seems that the same effect occurred in the high MHD discharge 18369 shown in figure 2 and in the improved confinement examples of discharges 24126 and 24128, figure 1.

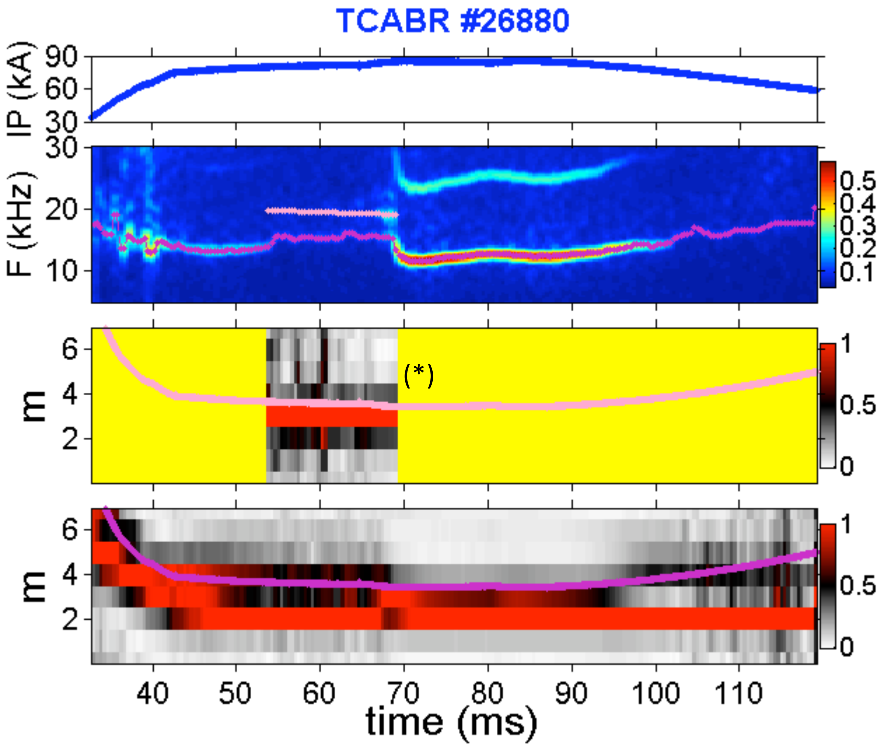


Figure 4 Plasma current, I_p, spectrogram of MHD activity measured with Mirnov coils, and two spectrograms of the poloidal mode number for discharge 26880 in TCABR. Spectogram (*) corresponds to the mode with higher frequency observed in the interval The pink trace in the last two figures corresponds to the value of the edge safety factor.

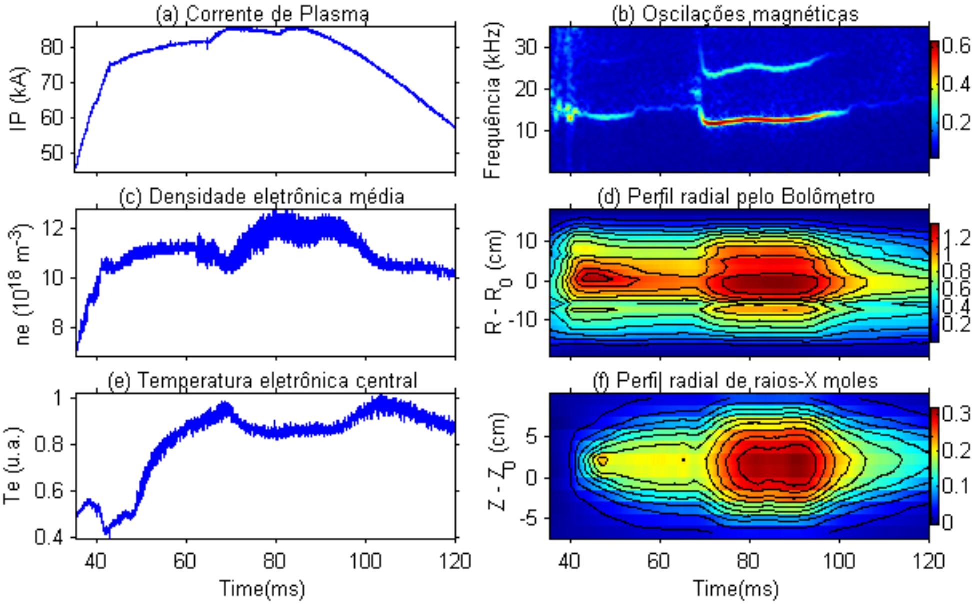


Figure 5 Plasma current, I_p, plasma density, n_e, central electron temperature, T_e, spectrogram of MHD activity measured with Mirnov coils, and spectrogram of the emission measured by the bolometer and X-ray diagnostics for discharge 26880 in TCABR.

3. Measurement of plasma rotation

A somewhat original spectroscopic method to measure the rotation of the plasma column in TCABR was developed sometime time ago and it has been under permanent improvement ever since [8-11]. The method is based upon measuring simultaneously two distinct bands of the profile of an appropriate impurity emission line to estimate the Doppler shift due to rotation. The two main results obtained so far with this diagnostic were to show that the value of the poloidal plasma rotation agrees with the neoclassical predictions in the collisional regime [8,9] and that the toroidal rotation follows the same scaling verified in large tokamaks [12]. According to this scaling, the product of the plasma current by the maximum variation of the radial profile of the toroidal velocity is proportional to the same variation of the ion temperature profile.

Recently the system has been substantially improved to allow simultaneous measurements of the toroidal and poloidal components of the rotation velocity at one and two points, respectively. Details of the new system were presented in another paper in another paper in this conference [12]. With this system it was possible to confirm that direction of the toroidal component is mostly opposite to the plasma current inside the plasma, reverting direction close to the plasma boundary, whereas the poloidal component is in the electron diamagnetic drift velocity, as indicate in figure 6. The maximum value of the toroidal and poloidal components can reach 15 km/s and 6 km/s, respectively; actual experimental values are given in [12].

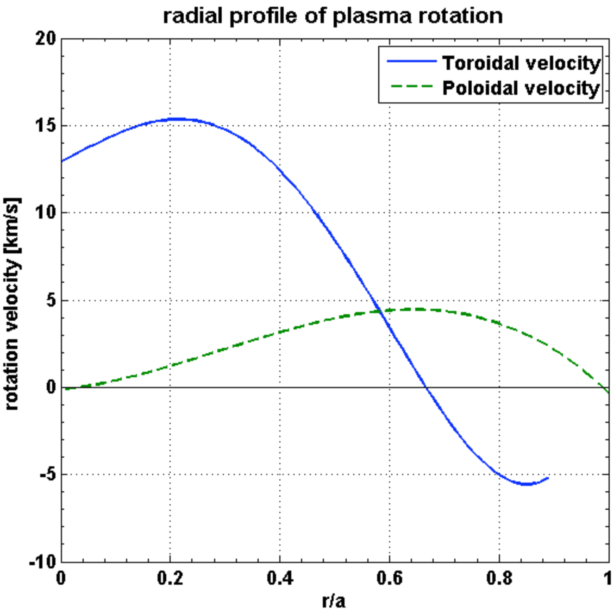


Figure 6 Sketch of the standard radial profiles of the toroidal and poloidal components of the plasma rotation velocity in TCABR discharges. For the toroidal component, positive means in the direction of the toroidal field (opposite to the plasma current) and for the poloidal component positive means in the electron diamagnetic drift velocity.

4. Long-range correlations and GAMs

It is currently accepted that zonal flows- ZFs and geodesical acoustic modes – GAMs play a quite relevant role on reducing the associate anomalous transport caused by turbulence [13,14]. For this reason there has been intensive theoretical and experimental investigation on the characteristics of these modes under different conditions and on their effects [15,16]. In standard fluid theory, the zonal flow and the geodesic acoustic mode in fact correspond to the zero and non-zero frequencies of the same dispersion relation, respectively. The frequency of the GAM is proportional to the ion sound speed and, for standard tokamak equilibria, it represents a continuum of singular stable perturbations on the magnetic surfaces.

Since both the ZFs and the GAMs have constant phases in the toroidal direction, one of the standard techniques to identify them experimentally, close to the plasma boundary, is to search for electrostatic perturbations with long-range correlations in the toroidal direction [17]. This method is being intensively used in TCABR using different types of electrostatic probes, located in different positions, as described Kuznetsov et al [18]. In this work it was clearly shown that electrostatic potential fluctuations with long distance correlations are substantially amplified during the transition to the improved confinement regime, triggered by electrostatic biasing of the plasma edge. Furthermore, for long toroidal distances between probes, the cross-spectrum is concentrated at low frequencies $f < 60$ kHz with three peaks observed at $f < 5$ kHz, $f = 13–15$ kHz and $f \approx 40$ kHz and low wave numbers with a maximum at $k = 0$. Careful analysis of data has shown that these peaks are indeed associated with electrostatic fluctuations, and not the result of MHD activity.

This result is somewhat surprising because one should expect only two peaks in the correlation spectra, one at rather low frequency, associated with ZFs, and another in the range of frequencies of the second peak, associated with GAMs. Although the precision in the determination of the lowest frequency peak is not good enough, due to the limitation on the maximum number of data points, it is definitely above 1 kHz. Nevertheless, a reasonable qualitative explanation for the occurrence of the three peaks can be put forward by taking into account recent theoretical developments on the effect of plasma rotation on the dynamics of GAMs.

Indeed, Elfimov and collaborators have shown that, for axisymmetric magnetic confinement configurations with isothermal flux surfaces and toroidal and poloidal rotation, there appears three solutions of the dispersion relation for GAMs [19]. The highest branch ω_1 corresponds to the standard GAM with a frequency up-shift,

$$\omega_1^2 = \frac{c_s^2}{R_0^2}\left[2 + \frac{1}{q^2} + 4M_t^2 - 4M_pM_t\left(1 - \frac{1}{q^2}\right) + M_p^2\left(2 - \frac{1}{q^2} + \frac{2}{q^4}\right)\right], \tag{1}$$

where c_s is the ion sound speed, R_0 is the major radius of the plasma column, q is the inverse rotational transform, and M_t and M_p are the toroidal and poloidal Mach numbers, respectively. The second branch,

$$\omega_2^2 = \frac{c_s^2}{q^2R_0^2}\left[1 - 4M_pM_t + M_p^2\left(3 - \frac{2}{q^2}\right)\right], \tag{2}$$

is driven by toroidal rotation, so that it does not exist in the limit $M_t \to 0$, due to a degeneracy in the dispersion relation.

These modes had already been obtained by other authors assuming different models for the flux surfaces [20]. However, a third low frequency mode is found for the isothermal flux surfaces, with frequency given by

$$\omega_3^2 = \frac{c_s^2}{q^2R_0^2}\left[M_p^2(1 - M_d)^2 + \frac{q^2(\gamma - 1)}{2(1 + 2q^2)}\left(M_t^2 - 2M_tM_p + 2M_p^2\right)M_t^2\right], \tag{3}$$

where M_d is a quantity that depends on the heat flux at the magnetic surface to warrant constant temperature [19].

The radial profile of these frequencies have been calculated from the relevant quantities measured for TCABR, in particular the rotation velocities, and the results are shown in figure 7. We see that, before the application of the biasing pulse on the external electrode, that is, in the ohmic phase of the discharge, only the MHD oscillations at f ≈ 16 kHz and its harmonics are observed. When biasing is applied, there appears three distinct peaks concentrated around the toroidal wave number k ≈ 0, i.e., quite distinct from the MHD modes have non zero k. The frequencies of these peaks agree well with the predictions from the theory presented in [19], as schematically indicated by the arrows.

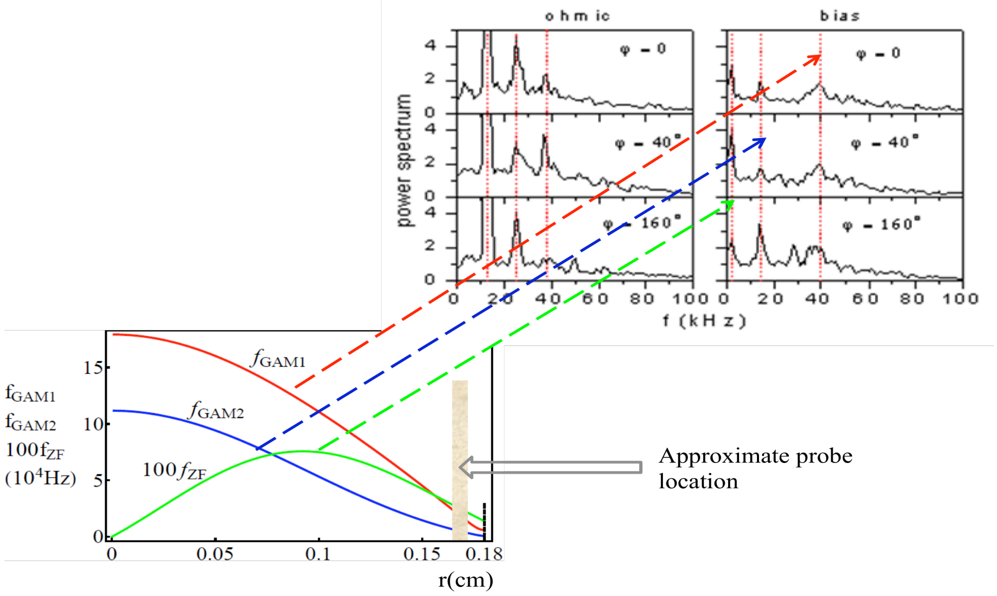


Figure 7 The three roots of the dispersion relation for GAMs, equations (1), (2), and (3), for actual parameters of the TCABR discharge, in an experiment with edge electrostatic biasing. The insert on the top is taken from figure 8 of [18]. The angle φ gives the toroidal location of the probes for which the cross-correlations are calculated.

5. Excitation of Global Alfvén Waves

The Global Alfvén Waves – GAWs are discrete modes that can be excited in axisymmetric magnetic confinement configurations below the Alfvén continuum [21,22]. They have been experimentally observed in PRETEXT [23] and TCA [24] and lately proposed to be used as a diagnostic tool to determine the inverse rotational transform q and the effective mass number in tokamaks [25]. However they are somewhat difficult to be excited in large tokamaks, due to effects of the Hall parameter (ω/ω_{ci}), where ω_{ci} is the cyclotron frequency, plasma pressure, and shear at the minimum value of q [26]. On the other, the so-called Toroidal Alfvén Eigenmodes – TAEs, which are also discrete modes but excited in the gaps of the continuum introduced by toroidal mode coupling, can be excited and have a deleterious effect on the confinement of alpha particles in large tokamaks [27].

The excitation of GAWs in carefully investigated in TCABR with two main purposes: its application as a diagnostic tool and to acquire know-how on the excitation and detection of TAEs in large tokamaks. The modes are excited using the same antennae used for Alfvén wave heating, but at low power ($\leq$ 1 kW) and are detected by two magnetic probes. The experimental setup is described in detail in another paper presented at this meeting [28]. The main results are shown in figure 8, which is the same of that work. The eigenmodes appear in four distinct bands, corresponding to different combinations of the poloidal n and toroidal m modes numbers, which are being carefully identified. The frequency in each band decreases inversely proportional to the square root of the density, as predicted by theory.

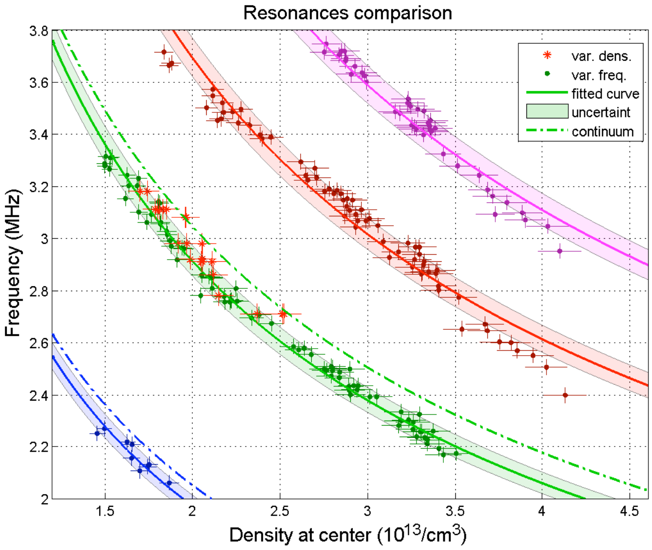


Figure 8. Summary of identified resonant frequencies over the estimated density at the center of the plasma. The dot-dash lines represent the Alfvén continuum minimum for effective mass number A=1.36 and density 1.15 times higher as the value shown on axis *n/m* = -1/-1 (blue) and -2/-1 (green).

6. Conclusions

The results of four lines of experimental work being currently carried out in TCABR have been summarized in this work. The effect of coupling between MHD modes on the influx of impurity, which affects the performance of improved confinement regimes triggered by edged electrostatic biasing, has been clarified. The radial profiles of the poloidal and toroidal rotation of the plasma column have been determined and it has been shown that, in the presence of rotation, the three branches of the GAMs that were theoretically predicted agree well with experimental measurements of long distance electrostatic potential fluctuations at the edge of the plasma column. Finally, a detailed investigation of the excitation of GAWs has been carried out and the results are in good agreement with theoretical predictions.

Acknowledgements

This work was supported by FAPESP (Research Foundation of the State of São Paulo), grant 2011/50773-0, and by CNPq (National Council for Scientific and Technological Development), grants 307511/2011-1 and 480733/2013-9.

References

[1] TCA Team 1985 *Nuclear Fusion* **25** 1041
[2] Campos D O, Elizondo, J I, Fagundes A N, Ferreira A A, Galvão R M O, Kuznetsov Yu K, Nascimento I C, Ruchko L F, Severo J H F and Vannucci A 2000 *Proceedings of the 2000 International Congress on Plasma Physics - Contributed Papers. Quebec*
[3] Galvão R M O, Bellintani V, Bengtson R D, Elfimov A G, Elizondo J I, Fagundes A N, A Ferreira A A, Fonseca A M M, Kuznetsov Y K, Lerche E A, Nascimento I C, Ruchko L F, de Sa W P, Saettone E A S, Sanada E, Severo J H F, da Silva R P, Tsypin V S, Usuriaga O C and Vannucci A 2001 *Plasma Phys. Control. Fusion* **43** A299
[4] Weynants R R, Jachmichz S and G Van Oost 1998 *Plasma Phys. Control. Fusion* **40** 635

[5] Nascimento I C, Kuznetsov Yu K, Severo J H F, Fonseca A M M, Elfimov A G, Bellintani V, Machida M, Heller M VA P, Galvão R M O, Sanada E and Elizondo, J I 2005 *Nuclear Fusion* **45** 796

[6] Nascimento I C, Kuznetsov Yu K, Guimarães-Filho Z O, El Chamma-Neto, Usuriaga O, Fonseca A M M, Galvão R M O, Caldas I L, Severo J H F, Semenov I B, Ribeiro C, Heller M VA P, Bellintani V, Elizondo, J I and Sanada E 2007 *Nuclear Fusion* **47** 1570

[8] Severo J H F, Nascimento I C, Tsypin V S and Galvão R M O 2003 *Nuclear Fusion* **43** 1047

[9] Severo J H F, Nascimento I C, Tsypin V S, Kuznetsov Yu K, Saettone E A S, Vannucci A, Galvão R M O, Tendler M and Mikhailovskii A B 2004 *Physics of Plasmas* **11** 846

[10] Severo J H F, Nascimento I C, Kuznetsov Yu K, Tsypin V S, Galvão R M O and Tendler M 2007 *Review of Scientific Instruments* **78** 043509

[11] Severo J H F, Nascimento I C, Kuznetsov Yu K, Galvão R M O, Guimarães-Filho Z O, Borges F O, Usuriaga O C, Elizondo, J I, de Sa W P, Sanada E K, and Tendler M 2009 *Nuclear Fusion* **49** 115026

[12] Ronchi G, Severo J H F, Sá W P and Galvão R M O 2014 *Data Acquisition and Automation for Plasma Rotation Diagnostic in the TCABR Tokamak*, submited to J. Phys.: Conf. Series.

[13] Lin Z, Hahm T S, Lee W W, Tang W M and White R B 1998 *Science* **281** 1835

[14] Diamond P H, Itoh S-I, Itoh K and Hahm T S 2005 *Plasma Phys. Control. Fusion* **47** R35

[15] Burrell K.H. 1997 *Phys. Plasmas* **4** 1499

[16] Fujisawa A 2009 *Nucl. Fusion* **49** 013001

[17] Xu Y, Jachmich S, Weynants R. R, Van Schoor M, Vergote M, Kraemer-Flecken A, Schmitz O, Unterberg B and Hidalgo C 2009 *Phys. Plasmas* **16** 110704

[18] Kuznetsov Yu K, Nascimento I C, Silva C, Figueiredo H, Guimarães-Filho Z O, Caldas I L, Galvão R M O, Severo J H F, Toufen D L, Ruchko L F, Elfimov A G, Elizondo, J I, de Sa W P, Usuriaga O C, *et al* 2012 *Nucl. Fusion* **52** 063004

[19] Elfimov A G, Galvão R M O and Sgalla R J F 2011 *Plasma Phys. Control. Fusion* **53** 105003

[20] Ilgisonis V I, Lakin V P, Smolyakov A I and Sorokina E A 2011 *Plasma Phys. Control. Fusion* **53** 065008

[21] Appert K, Balet B, Vaclavik J 1982 *Physics Letters A* 233

[22] Ross D W, Chen G L and Mahajan S M 1982 *Phys. Fluids* **25**, 652

[23] Evans T E, Valanj P M, Benesch J F, Bengston R D, Li Y M, Mahajan S M, Oakes M E, Ross, D W, Wang X Z and Watkins J G 1984 *Phys. Rev. Lett.* **53** 1743

[24] Collins G A, Hofmann F, Joye B, Keller R, Lietti A, Lister J B and Pochelon A 1986 *Physics of Fluids* **29**, 2260

[25] Holties H A, Fasoli A, Goedbloed J P, Huysmans G T A and Kerner W 1997 *Phys. Plasmas* **4**, 709

[26] Elfimov A G 2008 *Phys. Plasmas* **15**, 074503

[27] Fasoli A, Borba D, Gormezano C, Heeter R, Jaun A, Jacquinot J, Kerner W, King Q, Lister J B, Sharapov S, Start D and Villard L 1997 *Plasma Phys. Control. Fusion* **39**, B287

[28] Puglia P G P, Elfimov A G, Ruchko L F, , Galvão R M O, Guimarães-Filho Z O, Ronchi G, Fonseca A M M, , Kuznetsov Yu K, Nascimento I C, Reis A P, de Sá W P, Sanada E K, Severo J H F, Theodoro V C and Elizondo J I O 2014 *Excitation of Global Alfvén Waves by Low RF Power on TCABR*, submited to J. Phys.: Conf. Series.