Universidade de São Paulo

Instituto de Física

Spectral analysis from experimental data for search of
geodesic low frequency modes in the Tokamak TCABR

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Master dissertation presented
to Institute of Physics
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Examination Commission :

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São Paulo, 2013

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Analise espectral de dados experimentais em busca de
modos geodésicos de baixa frequência no Tokamak TCABR

Wilson Andres Hernandez Baquero

Orientador: Prof. Dr. Ricardo Magnus Osorio Galvão

Dissertação de mestrado apresentada
ao Instituto de Física
para a obtenção do título
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A las personas que quiero....

En el libro X de su Historia, Plinio declara que la salamandra es tan fría que apaga el fuego con su simple contacto; en el XXI recapacita, observando incrédulamente que si tuviera esta virtud que le han atribuido los magos, la usaría para sofocar los incendios. En el libro XI, habla de un animal alado y cuadrúpedo, la pyrausta, que habita en lo interior del fuego de las fundiciones de Chipre; si emerge al aire y vuela un pequeño trecho, cae muerto. El mito posterior de la salamandra ha incorporado el de ese olvidado animal.

El libro de los seres imaginarios, La salamandra, Jorge L. Borges & Adolfo B. Casares.

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To my friends.

To Luisa.

To my father, my mom, my sister, my brother, my niece

Resumo

O objetivo do presente estudo é a procura de evidências da presença de modos GAM nas descargas do tokamak TCABR, em distintos regimes de operação. As descargas selecionadas foram classificadas segundo a maneira de obter a melhora no confinamento do plasma. Nós fizemos essa procura nas descargas ôhmicas com incremento espontâneo da densidade do plasma, em descargas onde o plasma foi perturbado externamente pela injeção de ondas de Alfvén e pela alteração do campo elétrico radial via eletrodo de *bias*. Por causa da natureza eletrostática da oscilação GAM, nas descargas selecionadas foi relevante a presença das sondas eletrostáticas (conhecidas também como sondas de Langmuir). As bobinas de Mirnov foram importantes para identificar as oscilações MHD. Diversos métodos de análise espectral e estatístico foram usados na análise dos sinais experimentais como ajuda para identificar os modos GAM. Os métodos usados foram: correlação, espectro de auto-potência, espectro de potência cruzado, coerência e densidade espectral em número de onda e frequência. Para as bobinas de Mirnov, só o espectro de auto-potência foi usado. Os resultados da análise realizada nas descargas com crescimento espontâneo da densidade e nas descargas aquecidas com ondas de Alfvén, não mostram nenhuma presença de GAMs. Nessas descargas somente ocorreu um pequeno incremento na correlação que foi causado pela atividade MHD. Para as descargas com *bias*, a análise mostra a presença de um modo de $f \sim 40\text{KHz}$, modo que não se observa nas bobinas de Mirnov e que tem simetria poloidal e toroidal.

Abstract

The goal of the present study is to search for evidences of the presence of GAM modes in plasmas discharges of the TCABR tokamak at different operational regimes. The selected discharges were classified according to the way used to obtain plasma improvement of confinement. We perform this search in pure ohmic discharges with a spontaneous increment of the plasma density and in discharges where the plasma was externally perturbed by the injection of Alfvén waves and by electrostatic edge biasing. Given the electrostatic nature of the GAM oscillation, in the selected discharges were relevant the presence of electrostatic probes (also known as Langmuir probes). The signals from Mirnov coils was important too, for identify the MHD oscillations. Several statistical and spectral methods were used to analyze the experimental signals in order to helps the identification of the GAM modes, correlation, auto-power spectra, cross-power spectra, coherence and spectral density in wave number and frequency ($S(k, f)$). For the Mirnov coil just auto-power spectra was used. The results of the analysis performed on the discharges with spontaneous increase of density and for those with Alfvén heating did not show any presence of GAMs. There was just an few increment of the correlation but it was due to the MHD activity. For the discharges with edge biasing, the analysis shows the presence of a $f \sim 40\text{kHz}$ mode that was not present in the Mirnov coil and that has toroidal and poloidal symmetry.

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Introduction

The tokamak is a device developed in the 50's in the Soviet Union with the objective of creating a reactor to achieve thermonuclear fusion of deuterium and tritium. After decades of investigation an international engineer project for a prototype of nuclear reactor has been developed. This project is leaded for th USA, EU, Russia, Japan, China, South Korea and India. The ITER (International Thermonuclear Experimental Reactor) will be build in France and will establish the bases for the use of thermonuclear fusion as a real alternative for an energy source for the humanity. The tokamak is a toroidal system that uses an equilibrium toroidal current as an initial heating system. The heating is achieved by means of the Joule effect. However the anomalous transport of energy and particles in magnetic confinement plasmas yields a characteristic confinement time one or two orders of magnitude smaller than the theoretical predictions, via neoclassical transport theory. The turbulence, created by many instabilities, generates an anomalous loss of energy of the plasma column. When the exterior becomes cooler, there is a penetration of impurities, increasing the losses due to radiation and changing of the plasma conditions, generating instabilities in the plasma column that finally leads to a disruption. An improvement confinement regime called H mode (High Confinement) was discovered in the ASDEX tokamak [1], where the confinement was improved by a factor of nearly two with respect to normal confinement or L mode (Low confinement). After its discovery this mode was found in different tokamaks, using several heating methods. In the TCABR two methods are used for controlling the anomalous transport and the magnetohydrodynamics (MHD) instabilities in the plasma column [2]. The first referred as electrostatic bias, is the electric polarization at the edge of the plasma for inducing a change in the radial electric field. In the second technique, an RF signal is excited in the plasma by an antenna; this RF field is coupled to the KAW (Kinetic Alfvén Waves) that dissipates on the electrons.

It was experimentally discovered that the transition from L to H mode was accompanied by geodesic mode or regular oscillations called GAM (geodesic Acoustic Mode)[3]. These GAMs are electrostatic modes, which are generated due to the toroidal curvature R of the magnetic field $\mathbf{B}$ on the flux surface. This mode has a frequency proportional to the ion acoustic veloc-

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ity [4], and can be detected using several diagnostics, like: [5] electrostatic probes, heavy ion beam probes (HIBPs), beam emission spectroscopy (BES), and (Doppler) reflectometry. In the TCABR tokamak there was presented the existence of a suspected GAM mode in the 40kHz frequency by Kuznetsov et al.[6] where the analysis was based on data of electrostatic probes.

The objective of this work is show the results of a search in the TCABR discharges database for the GAMs. The analysis of the experimental data from the electrostatic probes was based on correlation and spectrogram techniques developed in MATLAB.

The search of the GAMs in the discharges heated by Alfvén waves gave a negative result and the basic analysis is concentrated in the bias discharges where the results were positive. results for this class of discharges, and analysis was did for bias discharges where the result was positive. The text is divided into four chapters. In chapter 1 it is presented an introduction to thermonuclear fusion and plasma confinement; in the chapter 2 the basic theory of the electrostatic probes and the correlation and spectral techniques used in the data analysis are presented. Chapter three gives a description of the theory of GAMs and its basic features. In chapter 4 the results obtained from the analysis of data form relevant TCABR discharges are present. Finally the conclusions and perspectives are discussed.

Chapter 1

Plasma and fusion

The plasma is called the fourth state of matter, because it has properties that are different from that of solid, liquid, or gas. The different behavior lay in the phenomena produced by electromagnetic that act in a different way in plasmas.

Although not present in the everyday life (just in lightning bolt, neon or fluorescent light, some pc screens), at least 99% of the visible universe is plasma; the stars and nebulae has also it matter component in the plasma state. The fact that explains that is the Saha equation

$$\frac{n_i}{n_n} = 2.4 \times 10^{15} \frac{T^{3/2}}{n_i} \exp\left(-\frac{U_i}{KT}\right) \quad (1.0.1)$$

where n_i and n_n are the number of ionized and neutral atoms per cm^3 , T the temperature of the gas in Kelvin, K the Boltzmann constant and U_i the ionization energy in ergs. Using the values of normal conditions on the surface of the earth, that is $T \approx 300K$, $n_n \approx 3 \times 10^{19}$ and using the ionization energy of the nitrogen (78% of atmospheric composition) the result is that by each ionized atom there are 10^{122} neutral atoms, a very low percentage of particles in the air are ionized therefore plasma phenomena is not appreciable under normal conditions on earth surface.

One of the main interest in plasma study is the application of generation of energy by nuclear fusion because of the low pollution produced in the process.

1.1 Definition of plasma

A definition given by [7] states that:

"A plasma is a quasineutral gas of charged and neutral particles which exhibits collective behavior"

Following this we have that there are two important concepts, quasineutral and collective behavior. The concept of collective behavior can be understood in the following way. When the gas is neutral, as air at atmospheric conditions, an external force can affect the particles just by collisions. However, in the case when there is a considerable amount of free charges, the Coulomb forces can act, as seen in the figure 1.1. In the volume A there will be an electric force that decreases as $1/r^2$, but the volume that contains the charge volume B increases as r^3 for a constant solid angle. Then in the test the volume A there will be a force induced by distant regions in the plasma. The second aspect is the concept of "quasi neutral". An important

Figure 1.1: Long range interactions in plasma. [8]

property of the plasma is its capacity of shield external electric potentials, because the free charges in the plasma. Because of the finite temperature, in a certain limit where the thermal energy is of the order of the potential energy, there will not be a perfect shielding; some particles can have sufficient energy to escape from potential well. To calculate the approximate value of the thickness of this layer we suppose the following model. In $x = 0$ a perfect transparent grid is held at potential ϕ_0 . Assuming that the ions to electrons mass ratio m_i/m_e , is infinite, then the ions will be glued to a uniform background. Then the idea is to calculate the unidimensional potential $\phi(x)$. First we have the Poisson's equation

$$\nabla^2 \phi = \frac{d^2 \phi}{dx^2} = -4\pi e(n_i - n_e) \quad (1.1.1)$$

far away from the grid, the density of the ions is $n_i = n_\infty$. For electrons we have that the density of electrons, for a Maxwell's distribution of the velocities, is

$$n_e = n_\infty \exp\left(\frac{e\phi}{KT_e}\right) \quad (1.1.2)$$

where e is the elemental charge, T_e the temperature of the electrons, and K the Boltzmann constant. Now, in the region where $|e\phi/KT_e| \ll 1$, using

the expansion in Taylor's series for the density of the electrons in the equation 1.1.1 it follows that

$$\frac{d^2\phi}{dx^2} = 4\pi en_\infty \left[\frac{e\phi}{KT_e} + \left(\frac{1}{2} \frac{e\phi}{KT_e} \right)^2 \right] + \dots \quad (1.1.3)$$

then keeping the linear terms only, the following differential equation is obtained

$$\frac{d^2\phi}{dx^2} = \frac{4\pi n_\infty e^2}{KT_e} \phi. \quad (1.1.4)$$

This equation has a solution given by

$$\phi = \phi_0 \exp \left(\frac{-|x|}{\lambda_D} \right), \quad (1.1.5)$$

where λ_D is the so called Debye length, defined as

$$\lambda_D = \sqrt{\frac{KT_e}{4\pi n e^2}}. \quad (1.1.6)$$

There are three important points. The first is that the length of the sheath increases with the temperature; because of the major thermal energy, second, if the density is higher the sheath is thinner, there are more charges for the shielding. Third, the thermal temperature is that from the electrons, as we have supposed that the inertia of the ions is so big that they are practically fixed in the shielding process.

Now that we have a Debye length parameter, it is possible to define the conditions under which we can treat a ionized gas as a plasma. For a ionized gas have plasma properties as "collective behavior" the system has to be bigger than λ_D

$$\lambda_D \ll L \quad (1.1.7)$$

Supposing a sphere of radius λ_D , the number of particles in this volume is

$$N_D = \frac{4}{3} n \pi \lambda_D^3 \quad (1.1.8)$$

and a new condition is needed for a plasma behavior is

$$N_D \gg 1 \quad (1.1.9)$$

what justifies a statistical treatment. The final parameter is based on the occurrence of collisions. If the mean time collisions is τ , the frequency ω of a wave in the plasma has to be bigger than collision frequency, i.e.

$$\omega\tau \gg 1 \quad (1.1.10)$$

If this parameter is not reached, the behavior of the gas will be just that of a fluid where the collisions determine the phenomena. Then the equations (1.1.7), (1.1.8) and (1.1.10) give the conditions for an ionized gas be treated as a plasma.

1.2 Nuclear fusion

The production of energy in the fusion reaction is based in the conversion of mass to energy according to Einstein equation. Then if we have

$$A + B \rightarrow C + D \quad (1.2.1)$$

and the process is of the form

$$(m_A + m_b)c^2 > (m_C + m_D)c^2 \quad (1.2.2)$$

there will be a quantity of energy released. In the case of the fusion reactions, the more interesting reaction for future use in energy production is

$$D^2 + T^3 \rightarrow He^4(3.5MeV) + n(14.1MeV) \quad (1.2.3)$$

In this process, the initial matter is deuterium and tritium and the products of the reaction are charged α particles (He^4) confined by a magnetic field, which could be reused for heating the plasma, and a neutron of high energy that can not be confined, but can be trapped in a surrounding blanket of Li^6/Li^7 . The blanket is heated by the neutrons making possible obtain energy and in the process there will breed T^3 for new fusions.

The initial combustible for the reaction can be obtained from the ocean water. In the ocean there are 6000 molecules of normal water for every molecule of deuterium water; then every liter of water can produce near 10^{10} J of energy. The tritium is obtained from the lithium, a relatively abundant metal, it is produced irradiating lithium with neutrons where can be used the product of the fusion reaction. To obtain the fusion reaction for energy production the plasma has to be approximately in the following conditions.

Table 1.1: Parameters for nuclear fusion [8]

Temperature T	10^8 K (10KeV)
Particle density n	$10^{21}m^{-3}$
Power density	$10MWm^{-3}$
Time scale τ	100s

Parameter approximated for obtain reliable energy from nuclear fusion in plasma.

1.3 Plasma confinement

As seen in table 1.1, the parameters for a thermonuclear reactor include high temperature and high density of the plasma for a relatively long time. Then for a viable nuclear fusion reactor a technical problem arises, the necessity of plasma confinement, because there is no material that support the requirements for the vacuum vessel under these conditions. The best solution to this problem is magnetic confinement. There are several kind of installations that could make possible to obtain the thermonuclear conditions shown in table 1.1, which are tokamaks, open traps, and different pinches.

Although there are several ways to reach the necessary confinement, the more promising way to do that is the TOKAMAK system¹, that is expected to be proved in ITER, an international effort for obtain sustainable plasma confinement at the fusion parameters for energy production. The main idea of the tokamak concept is to joint two ways of plasma confinement, the z-pinch and the θ -pinch, both cylindrical devices. The z-pinch is made by creating

Figure 1.2: z-pinch, θ -pinch and the mixture of the two ideas, the tokamak [8]

a toroidal current in the plasma, then a magnetic field in the poloidal direction is generated (figure 1.2), and the Lorentz force is $\mathbf{J} \times \mathbf{B} = -J_z B_\theta \mathbf{e}_r$,

¹The word tokamak is a transliteration of the Russian word токамак, an acronym of "тороидальная камера с магнитными катушками" (toroidal'naya kamera s magnitnymi katushkami) - toroidal chamber with magnetic coils.

produces a force in the inward radial direction. The problem is that the equilibrium is fragile, and the plasma blows up in a time scale of the order of μs . Another way for magnetic confinement is the θ -pinch, figure 1.2. In this case a current in the poloidal direction is generated, the toroidal field produced creates a Lorentz force in the inward radial direction. But in this case the system has instability forces that act on the end of the device, blowing up the plasma in the μs scale. A more reliable solution is to join the two ways of confinement in one device of toroidal geometry instead cylindrical, a tokamak, as seen in the figure 1.2. In the tokamak the two fields, toroidal and poloidal, are added to create a bended total field on the toroidal surfaces; in this case the system is more stable. The first device was constructed in the USSR in the 1950's and since then the time of confinement has been elevated from μ -seconds to minutes. The basic idea of the device as shown

Figure 1.3: z-pinch, θ -pinch and the mixture of the two ideas, the tokamak [8]

in the figure 1.3, in to induce a toroidal plasma current that generates the poloidal magnetic field, becoming the plasma the secondary of a transformer. The toroidal magnetic field is produced by an external array of coils along the toroid. The toroidal component of the field is larger than poloidal one for stability issues. One important parameter of the tokamak is the safety factor, which is responsible for the local and global stability of magnetized plasmas with the current

$$q = \frac{aB_{tor}}{RB_{pol}} \quad (1.3.1)$$

where a and R are the minor and major radii of the torus, respectively, in standard tokamaks the ratio between these values has to be maintained above 2 for stability.

1.4 The TCABR tokamak

The TCABR tokamak was designed and construed in Ecole Polytechnique de Lausanne/Switzerland with the main objective to study heating using Alfvén waves. After several years of investigation, the tokamak was transferred to Brazil, where a series of improvements were made, including the installation and actualization of several plasma diagnostics as Mirnov coils, electrostatic probes, soft and hard X ray detectors etc. The basic parameters of the TCABR are in table 1.2

Table 1.2: Parameters of the TCABR tokamak

Major radius R_0	0.61m
Minor radius a	0.18m
Plasma Current I_P	120KA
Shot time T_S	120ms
Central temperature of the electrons T_e	500eV
Central density of the electrons n_e	$6 \times 10^{19} \text{m}^{-3}$
Toroidal magnetic field B_φ	1.2T

Values of the basic parameters of the TCABR tokamak.

Chapter 2

Mathematical tools and experimental devices

In this chapter is presented an introduction to the tools of data analysis used in this work and a description of the physical principle of the electrostatic probe or Langmuir probe. The main tools used in this work were the correlation and the spectral analysis for which an introduction is presented in the section 2.1. Then in section 2.2 is presented an exposition of the physical principle for the electrostatic probe. The electrostatic probe was the device used to collect information from the plasma for the detection of GAMs due to electrostatic nature of this oscillations.

2.1 Data analysis tools

2.1.1 Correlation

Given two signals $\phi_1(t)$ and $\phi_2(t)$ the correlation is a tool in signal processing to measure the likeness between them. It is defined as

$$C_{12} = \frac{\langle [\phi_1(t) - \bar{\phi}_1(t)] [\phi_2(t) - \bar{\phi}_2(t)] \rangle}{\sqrt{\langle [\phi_1(t) - \bar{\phi}_1(t)]^2 \rangle \langle [\phi_2(t) - \bar{\phi}_2(t)]^2 \rangle}} \quad (2.1.1)$$

where the operator $\langle \rangle$ refers to the expected value and the bar represents the mean value of the data. The correlation function goes from 0 when the data has not statistical relation, to ± 1 where the two signals are totally correlated and their phase is zero ($+1$) the two signals are totally correlated but have a phase π (-1). For example when the two signals are the same the correlation is 1.

2.1.2 Spectral analysis

In this work there were used two kinds of spectral analysis. In the first kind, the main quantities are the power spectra, the cross power spectra, and the coherence, which are functions just of the frequency. The second kind utilizes the spectral density in wavenumber and frequency $S(k, \omega)$, a function of the two variables, the wave number k and the frequency f or angular frequency ω . The frequency and angular frequency are related as $\omega = 2\pi f$.

Cross-power spectra and coherence

The first method is just a frequency analysis. Let us use a fast Fourier transform (FFT) in the signals $\phi_1(t)$ and $\phi_2(t)$ this procedure generate $\Phi_1(\omega)$ and $\Phi_2(\omega)$. Using this transformations, the cross-power spectrum is computed as

$$P_{12}(\omega) = \Phi_1^*(\omega)\Phi_2(\omega) \quad (2.1.2)$$

where the asterisk is used for the complex conjugate. When in the cross-power definition we use the same signal, we have an auto-power spectra

$$P_{11}(\omega) = \Phi_1^*(\omega)\Phi_1(\omega) \quad (2.1.3)$$

$$P_{22}(\omega) = \Phi_2^*(\omega)\Phi_2(\omega) \quad (2.1.4)$$

In the case of the cross-power spectra in 2.1.2, the result is in general a complex function, that can be decomposed into the real and imaginary parts

$$P_{12}(\omega) = C_{12}(\omega) + iQ_{12}(\omega) \quad (2.1.5)$$

where C and Q are the real and imaginary parts, respectively. Alternatively $P_{12}(\omega)$ can be represented as a norm and phase

$$P_{12}(\omega) = |P_{12}(\omega)| \exp(i\alpha_{12}(\omega)) \quad (2.1.6)$$

where $|P_{12}(\omega)|$ is the cross-amplitude spectrum and $\alpha_{12}(\omega)$ is the phase spectrum. Another quantity of interest is the coherence spectrum, which is defined in terms of the auto-power and the cross-power spectra as

$$|\gamma_{12}(\omega)| = \frac{|P_{12}(\omega)|}{\sqrt{|P_{11}(\omega)||P_{22}(\omega)|}} \quad (2.1.7)$$

The coherence gives the degree of correlation between the signal $f_1(t)$ and $f_2(t)$ for each frequency, ignoring the phase differences. The range of the coherence function is $[0, 1]$ where 1 represent mutual coherence, and 0 total incoherence between the oscillations of the two signals at the frequency ω .

Spectral density in wave number and frequency SKF

The method for the determination of the spectral power as a function of the wave number k and the frequency ω was developed by Beall et al. [9]. For this method the signals of two near probes are required; in this case we will label these probes as "1" and "2". Here is considered a signal with zero mean, stationary and homogeneous. This signal has a Fourier transformation in the time interval T and space interval L of the form

$$\Phi(x, \omega) = \int_{-T/2}^{T/2} dt \phi(x, t) \exp(-i\omega t) \quad (2.1.8)$$

$$\Phi(k, \omega) = \int_{-L/2}^{L/2} dx \phi(x, \omega) \exp(-ikx). \quad (2.1.9)$$

The cross spectral density $H(\chi, \omega)$ and the spectral density $S(k, \omega)$ are defined as

$$H(\chi, \omega) = \lim_{T \rightarrow \infty} \frac{1}{T} \langle \Phi^*(x, \omega) \Phi(x + \chi, \omega) \rangle \quad (2.1.10)$$

$$S(k, \omega) = \lim_{L, T \rightarrow \infty} \frac{1}{LT} \langle |\Phi(x, \omega)|^2 \rangle, \quad (2.1.11)$$

where the bracket as usual denotes the expected value. From the previous definitions and the translation properties of Fourier transform we have

$$H(\chi, \omega) = \frac{1}{2\pi} \int dk S(k, \omega) \exp(ik\chi) \quad (2.1.12)$$

and in the especial case of $\chi = 0$ we have

$$H(0, \omega) = \lim_{T \rightarrow \infty} \frac{1}{T} \langle \Phi^*(x, \omega) \Phi(k, \omega) \rangle = S(\omega) \quad (2.1.13)$$

where $S(\omega)$ is the spectral density

$$S(\omega) = \int dk S(k, \omega) \quad (2.1.14)$$

In the case when $\phi(x, t)$ is a solution of a deterministic differential equation or when only the amplitude of the signal is a random function, knowing the dispersion relation $k(\omega)$, it is possible to obtain the spectral density as

$$S(k, \omega) = S(\omega) \delta[k - k(\omega)] \quad (2.1.15)$$

However, if there is not a deterministic relation between k and ω , then the power in a band of frequencies is narrow in the wave number domain. This is the case when the method is useful. Then, we first need to introduce the "conditional" wavenumber spectral density

$$s(k|\omega) = \frac{S(k, \omega)}{S(\omega)}. \quad (2.1.16)$$

This function involves the idea of conditional probability

$$P(A|B) = \frac{P(A, B)}{P(A)} \quad (2.1.17)$$

that gives the probability of occurrence of B if A happens too. In the case of 2.1.16, the function can be interpreted as the power fraction at the frequency ω with wave number in the interval k to $k + \Delta k$. For signals of this kind, using equations 2.1.12 and 2.1.16, we have that

$$\frac{1}{i^n} \frac{1}{H(0, \omega)} \left(\frac{\partial^n H(\chi, \omega)}{\partial \chi^n} \right) \Big|_{\chi=0} = \int dk k^n s(k|\omega). \quad (2.1.18)$$

Based on the fact that Iwama *et al.* [10] developed a method to calculate the statistical moments using two probes separated by a distance χ_p . First we will need the polar representation of the Fourier transformation

$$\Phi(x, \omega) = a(x, \omega) \exp[i\theta(x, \omega)] \quad (2.1.19)$$

where

$$a(x, \omega) = |\Phi(x, \omega)| \quad (2.1.20)$$

$$\theta(x, \omega) = \tan^{-1} \left[\frac{\Im(\Phi(x, \theta))}{\Re(\Phi(x, \theta))} \right] \quad (2.1.21)$$

with the phase angle it is possible to obtain the local wavenumber in an approximate form, for the probes in positions x_1 and x_2

$$K(x, \omega) = \frac{\partial \theta(x, \omega)}{\partial x} \approx \frac{\theta(x_1, \omega) - \theta(x_2, \omega)}{x_2 - x_1}. \quad (2.1.22)$$

The point where the wavenumber is found is taken as the middle point between the probes

$$x = \frac{x_1 + x_2}{2} \quad (2.1.23)$$

Now using 2.1.23 and

$$\chi = x_2 - x_1 \quad (2.1.24)$$

the equation 2.1.18 becomes

$$\frac{\partial^n H(\chi, \omega)}{\partial \chi^n} \Big|_{\chi=0} = \lim_{T \rightarrow \infty} \frac{1}{T} \frac{\partial^n}{\partial \chi^n} \langle \Phi^*(x_1, \omega) \Phi(x_2, \omega) \rangle \Big|_{\chi=0}. \quad (2.1.25)$$

Using the polar representation in 2.1.25, we have for, $n = 0, 1, 2$, that

$$H(0, \omega) = \lim_{T \rightarrow \infty} \frac{1}{T} \langle a^2(x, \omega) \rangle \quad (2.1.26)$$

$$\left. \frac{\partial H(\chi, \omega)}{\partial \chi} \right|_{\chi=0} = \lim_{T \rightarrow \infty} \frac{1}{T} \langle a^2(x, \omega) K(x, \omega) \rangle \quad (2.1.27)$$

$$\left. \frac{\partial^2 H(\chi, \omega)}{\partial \chi^2} \right|_{\chi=0} = \lim_{T \rightarrow \infty} \frac{i^2}{T} \left[\langle a^2(x, \omega) K^2(x, \omega) \rangle + \left\langle \left(\frac{\partial a(x, \omega)}{\partial x} \right)^2 \right\rangle \right] \quad (2.1.28)$$

we can see from 2.1.26, 2.1.27 and 2.1.28 and using the fact that a turbulent medium can be modeled as a superposition of wave packets that satisfy the conditions

$$\left| \frac{1}{a(x, \omega)} \frac{\partial^n a(x, \omega)}{\partial x^n} \right| \ll |K^n(x, \omega)| \quad (2.1.29)$$

$$\left| \frac{1}{K(x, \omega)} \frac{\partial^n K(x, \omega)}{\partial x^n} \right| \ll |a^n(x, \omega)| \quad (2.1.30)$$

to despite the derived, that a general term of this for 2.1.25 is

$$\frac{1}{i^n} \left. \frac{\partial^n H(\chi, \omega)}{\partial \chi^n} \right|_{\chi=0} = \lim_{T \rightarrow \infty} \frac{1}{T} \langle a^2(x, \omega) K^n(x, \omega) \rangle \quad (2.1.31)$$

Finally assuming that the functions $a^2(x, \omega)$ and $K(x, \omega)$ are related by a joint probability density function $f(a^2, K; \omega)$ the statistical moments can be expressed as

$$\lim_{T \rightarrow \infty} \frac{1}{T} \langle a^2(x, \omega) K^n(x, \omega) \rangle = \lim_{T \rightarrow \infty} \frac{1}{T} \int \int da^2 dK a^2 K^n f(a^2, K; \omega) = \int dK K^n S_l(K, \omega) \quad (2.1.32)$$

where

$$S_l(K, \omega) = \lim_{T \rightarrow \infty} \int da^2 a^2(x, \omega) f(a^2, K; \omega) \quad (2.1.33)$$

has been defined as the *local wave number and frequency spectral density*. Using the result 2.1.32 in 2.1.31 and dividing by $S(\omega)$ we have

$$\frac{1}{i^n} \frac{1}{H(0, \omega)} \left. \frac{\partial^n H(\chi, \omega)}{\partial \chi^n} \right|_{\chi=0} = \int dK K^n s_l(K|\omega) \quad (2.1.34)$$

where

$$s_l(K|\omega) = \frac{S_l(K, \omega)}{S(\omega)} \quad (2.1.35)$$

finally we see from the method of Iwama et al. 2.1.18 and if the conditions 2.1.29 and 2.1.30 are valid that the local 2.1.33 and the "conditional" 2.1.16 wavenumber and frequency spectral density are the same.

For the implementation of the method the first step is to cut the acquired data in M segments of length T . The length has to be at least

$$T = \frac{2\pi}{\Delta\omega} \quad (2.1.36)$$

and the separation of the probes χ_p must be small enough to assure that

$$k = \frac{\pi}{\chi} \quad (2.1.37)$$

is greater than the highest wave number of interest. After taking this precautions the FFT algorithm

$$\Phi^{(j)}(x, \omega) = \frac{1}{N} \sum_{l=1}^N \phi^{(i)}(x, l\Delta t) \exp(-i\omega l\Delta t) \quad (2.1.38)$$

is calculated, from which it is possible to calculate the cross spectral density

$$H^{(j)}(\chi_p, \omega) = \Phi^{(j)*}(x_1, \omega) \Phi^{(j)}(x_2, \omega) = C^{(j)}(\omega) + iQ^{(j)}(\omega) \quad (2.1.39)$$

and the local wavenumber

$$K^{(j)}(\omega) = \frac{\theta^{(j)}(\omega)}{\chi_p} \quad (2.1.40)$$

with $\theta(\omega)$ given by

$$\theta^{(j)}(\omega) = \tan^{-1} \left[\frac{Q^{(j)}(\omega)}{C^{(j)}(\omega)} \right] \quad (2.1.41)$$

Finally, the local wavenumber and frequency spectrum are calculated as

$$\hat{S}_l(K, \omega) = \frac{1}{M} \sum_{j=1}^M I_{[0, \Delta k)}(K - K^{(j)}(\omega)) \times \frac{1}{2} [S_1^{(j)}(\omega) + S_2^{(j)}(\omega)] \quad (2.1.42)$$

where the function $I_{[0, \Delta k)}$ is defined as

$$I_{[0, \Delta k)}(K - K^{(j)}(\omega)) = \begin{cases} 1 & \Delta k \geq |K - K^{(j)}(\omega)| \\ 0 & \text{elsewhere} \end{cases} \quad (2.1.43)$$

Then the procedure is based on the values of the spectral powers for a given ω that are in the interval of wavenumber K to $K + \Delta K$.

2.2 Electrostatic probe

2.2.1 Plasma sheath

When a piece of material is immersed in a plasma, some layer appears around that piece, produced by the difference in the density of ions and electrons, forcing that the wall of the material reaches a negative potential with respect to plasma, this sheath is of the order of the λ_D . This effect is used as a base for a experimental diagnostic tool called the plasma probe or Langmuir probe. In this section we will calculate, in a approximated way following [11], the potential on the wall, the variation of the density and potential into the sheath, and a theoretical formula that shows the use of plasma probe to measure the density and temperature of plasma.

Basic ideas of the model

The basic physic idea of the phenomena is that as the particles of the plasma collide with the material, the ions recombine or return to the plasma. Meanwhile the electrons recombine or enter into the conduction band if the surface is a metal. Let us suppose that the particles have an isotropic distribution; in this case it follows from statistical mechanics that the number of particles that hit the surface is given by

$$\Gamma_\alpha = \frac{n_\alpha \langle v \rangle_\alpha}{4} \quad (2.2.1)$$

If we assume that the distribution of the particles is of Maxwell-Boltzmann type, the mean velocity is given by

$$\langle v \rangle_\alpha = \left(\frac{8}{\pi} \right)^{\frac{1}{2}} \left(\frac{kT_\alpha}{m_\alpha} \right)^{\frac{1}{2}} \quad (2.2.2)$$

where m_α and T_α are the mass and temperature of the α type particles, and k the Boltzmann constant. So we have that the particle flux is given by

$$\Gamma_\alpha = n_\alpha \left(\frac{kT_\alpha}{2\pi m_\alpha} \right)^{\frac{1}{2}} \quad (2.2.3)$$

An important fact appear in this equation; the flux is inverse to the mass. For this reason for the electrons the flux is larger than the flux of ions; then the result is a net accumulation of negative charges on the wall. As a consequence, the floating negative potential rises the flux of ions, in a way that a dynamical equilibrium is reached.

Electric potential on the wall

When the plasma sheath is created, we assume the following boundary conditions for the potential

$$\phi(x) = \begin{cases} \phi_w & \text{if } x = 0 \\ 0 & \text{if } x = \infty \end{cases} \quad (2.2.4)$$

where the reference is choose in the plasma. Using the results again from statistical mechanics we have that the densities the ions and electrons have are ¹

$$\begin{aligned} n_e(\mathbf{r}) &= n_0 \exp \left[\frac{e\phi(\mathbf{r})}{kT} \right] \\ n_i(\mathbf{r}) &= n_0 \exp \left[\frac{-e\phi(\mathbf{r})}{kT} \right] \end{aligned} \quad (2.2.5)$$

At dynamical equilibrium there is no more accumulation of charge; then the flux of ions and electrons have to balance

$$J_e(0) = J_i(0) \quad (2.2.6)$$

Using (2.2.1) and (2.2.5) and solving for the wall potential, we obtain

$$\phi_w = - \left(\frac{kT}{4e} \right) \ln \left(\frac{m_i}{m_e} \right) \quad (2.2.7)$$

Rewriting the last equation as

$$\frac{|e\phi_w|}{kT} = \frac{1}{4} \ln \left(\frac{m_i}{m_e} \right) \quad (2.2.8)$$

it is seen that the thermal and potential energy are of the same order, for example in the case of the Hydrogen the potential energy doubles that of thermal energy.

Inner structure of the plasma sheath

Continuing in the study of the inner structure, we write the conservation equations of particles and moment

$$\frac{dn_\alpha u_\alpha}{dx} = n_\alpha \frac{du_\alpha}{dx} + u_\alpha \frac{dn_\alpha}{dx} = 0 \quad (2.2.9)$$

$$m_\alpha u_\alpha \frac{du_\alpha}{dx} = - \frac{kT_\alpha}{n_\alpha} \frac{dn_\alpha}{dx} - q_\alpha \frac{d\phi}{dx} = 0 \quad (2.2.10)$$

¹At this point is depreciated the drift velocity of the particles towards the wall, this drift will be take in account with the hydrodynamic equations in the study of the inner structure of the sheath.

In the particle conservation equation (2.2.9), we use the fact that when the sheath is generated, the system is in dynamical equilibrium as in (2.2.6). In the case of the momentum conservation equation (2.2.10), the ideal gas behavior is assumed, and the collisions and magnetic fields are neglected. Now, the ions had a large mass and we assume that their thermal energy is low. For the electrons, because its low mass, the kinetic energy is low; then it is valid the assumption that

$$m_e u_e^2 \ll kT \ll m_i u_i^2 \quad (2.2.11)$$

Using this approximation in (2.2.9) and (2.2.10) we obtain

$$\frac{kT_e}{n_e} \frac{dn_e}{dx} - e \frac{d\phi}{dx} = 0 \quad (2.2.12)$$

$$m_i u_i \frac{du_i}{dx} + e \frac{d\phi}{dx} = 0 \quad (2.2.13)$$

Solving the equation 2.2.12 using the boundary conditions $n = n_0$ when $\phi = 0$ we have

$$n_e(\mathbf{r}) = n_0 \exp \left[\frac{e\phi(\mathbf{r})}{kT} \right] \quad (2.2.14)$$

that is equal to equation (2.2.5) because the drift velocity has not being taken into account. To solve the equation for ions (2.2.13,) we integrate; then

$$e\phi(x) + \frac{1}{2} m_i u_i^2(x) = C_2 \quad (2.2.15)$$

Now from the conservation equation (2.2.9)

$$n_i(x) u_i(x) = C_1 \quad (2.2.16)$$

where C_1 and C_2 are constants. Imposing the boundary conditions in the plasma $x \rightarrow \infty$ we must have $\phi(\infty) = 0$, $n_i(\infty) = n_0$, and $u_i(\infty) = u_{0i}$

$$n_i(x) = n_0 \left[1 - \frac{2e\phi(x)}{m_i u_{0i}^2} \right]^{-1/2} \quad (2.2.17)$$

Now we have a result that is different form (2.2.5). This variation has to result in a drift velocity for the ions. To obtain the electric potential into the sheath, Poisson's equation is used

$$\nabla^2 \phi = \frac{e}{\epsilon_0} (n_e - n_i) \quad (2.2.18)$$

and equations (2.2.14) and (2.2.17). Then it results the non-linear differential equation

$$\frac{d^2\phi}{dx^2} = \frac{n_0 e}{\epsilon_0} \left[\exp\left(\frac{e\phi}{kT}\right) - \left(1 - \frac{2e\phi(x)}{m_i u_0^2}\right)^{-1/2} \right] \quad (2.2.19)$$

To obtain an approximate solution for 2.2.19, we have the fact that, the potential near the plasma side of the sheath is going to 0; then, using $e\phi/kT \ll 1$ and expanding in Taylor's series

$$\exp\left(\frac{e\phi}{kT}\right) \simeq 1 + \frac{e\phi}{kT} \quad (2.2.20)$$

For the same reason it is possible to assume for the ions that $e\phi/(m_i u_0^2) \ll 1$; then using the Taylor expansion again

$$\left(1 - \frac{2e\phi(x)}{m_i u_0^2}\right)^{-1/2} \simeq 1 + \frac{2e\phi(x)}{m_i u_0^2} \quad (2.2.21)$$

Combining the results (2.2.20) and (2.2.21) we have a linear equation

$$\frac{d^2\phi}{dx^2} = \frac{\phi}{X^2} \quad (2.2.22)$$

where

$$X^2 = \lambda_D^2 \left(1 - \frac{2e\phi(x)}{m_i u_0^2}\right)^{-1} \quad (2.2.23)$$

Taking finally the boundary condition $\phi(\infty) = 0$, the result is

$$\phi(x) = A \exp(-x/X) \quad (2.2.24)$$

This solution is valid near the plasma side of the sheath and the constant has to be negative. Because the thermal energy of the ions is assumed less than the kinetic energy, $X \approx \lambda_D$ and the size of the sheath is of order of the Debye length. Assuming the validity of the solution on the wall, the constant A becomes ϕ_w . An important fact comes from (2.2.22) and (2.2.23); that if the value of the parameter X is imaginary, we have an oscillating solution, then there is no sheath. Finally we have that the solution requires that the so called Bohm criterion

$$kT < m_i u_0^2 \quad (2.2.25)$$

has to be satisfied for the creation of the plasma sheath.

2.2.2 Laungmuir probe or electrostatic probe

The plasma probe is a device used mainly to measure plasma's temperature and density. However, it can also be used to measure turbulent fluxes, by determining the correlations of floating potential fluctuations and the local density fluctuations by mean of the saturation current. The plasma probe is an electrode, immersed in the plasma, in which the potential and the current that flows are measured. The temperature and density are calculated using the equation deduced later. As we have seen, a sheath covers the surface of the probe, isolating the probe from the surrounding plasma. When no current² flows in the probe, we are in the dynamical equilibrium, then the probe has a floating potential ϕ_w . When the potential becomes negative, more electrons are repelled from the wall, and the net flux is due to the ions and, in that condition, we have a measurement of the current density J_i . When the potential becomes less negative or positive, the number of ions repealed rises and the net current becomes a electron current with density J_e . At a certain point the net current of ions (negative potential) or electrons (positive potential) reach a plateau, and we say that in that condition the probe reached the saturation current (of ions or electrons)³.

Figure 2.1: Characteristic curve of the probe [11] .

Now, let us calculate the equations for the temperature and density of the probe. From equation (2.2.5), we have that the density current out of the saturation region is

²The current is defined positive when it is away from the probe, then the electron current is considered positive.

³This saturation current is not predicted by the simple model used in this case

$$J_e = J_{e0} \exp\left(\frac{e\phi}{kT_e}\right) \quad (2.2.26)$$

We obtain from (2.2.3) that far away from the probe the current density is

$$J_{e0} = en_e \left(\frac{kT_e}{2\pi m_e}\right)^{1/2} \quad (2.2.27)$$

Then for the region where the potential is $\phi < 0$ the net current density is given by

$$J_p = J_{e0} \exp\left(\frac{e\phi}{kT_e}\right) - J_i \quad (\text{for } \phi < 0) \quad (2.2.28)$$

If this equation is solved for the temperature we obtain

$$T_e = \frac{e}{k} \left\{ \frac{d}{d\phi} [\ln(J_p + J_i)] \right\}^{-1} \quad (2.2.29)$$

Now, we are going to see how these results are used in an experiment. First, the ion saturation current, J_i , is obtained by using the negative exponential in the saturation region. Then is plotted the current in the probe as a function of the applied potential and using this scale, in the linear regions, it is possible to obtain the temperature using the slope, as seen in (2.2.29).

After the density of the electrons is calculated using (2.2.27), given the function

$$n_e = \frac{J_{e0}}{e} \left(\frac{2\pi m_e}{kT_e}\right)^{1/2}. \quad (2.2.30)$$

Then the two parameters of the plasma have been obtained.

Chapter 3

Geodesic acoustic mode GAM

3.1 Introduction

The Zonal Flows (ZF) have become an important issue of investigation because of the new paradigm in transport states that the turbulence is a dynamic and self-organized equilibrium of the ZF and drift waves [5]. The importance of this issue is related to the transition from L (Low) to H (High) confinement modes. In the ASDEX tokamak [1] in which it was shown that the that creation of a transport barrier (TB) was the cause of the improvement [12]. Moreover, the theoretical hypothesis was that [13] this TB is produced by sheared flow and experimental observations [14] show the relation between ZF and improvement in confinement for plasma fusion, in special for the ITER construction the prediction of turbulence is an important subject.

In tokamaks, the toroidal curvature of the flux surfaces causes a concentration of particle flux in the inner part of the surface, i.e., the flux on the flux surface becomes inhomogeneous in the poloidal direction. This effect is compensated by two phenomena that give rise to two different ZF. In the first, there appears a turbulence driven Stationary Flow. In the second, there appears an oscillation of the flow called Geodesic Acoustic Mode. The main characteristics of the two classes of ZF are showed in the table 3.1

Table 3.1: Resume of the characteristics of each class of ZF [5]

	Stationary Zonal Flows	GAM
Poloidal velocity	$v\theta(r)$	$v\theta(r)$
Toroidal velocity	$-2qv\theta(r)\cos(\theta)$	$(1/q)v\theta(r)\cos(\theta)$
Density fluctuations	~ 0	$\frac{\tilde{n}}{n} = \left(\sqrt{2}q_r\rho_s \frac{e\tilde{\phi}}{T_e} \right) \sin(\theta)$
Frequency	$\omega \sim 0$	$\omega \sim c_s/R$
Radial wavelength	$\lambda_r \sim \sqrt{a\rho_s}$	$\lambda_r \sim \sqrt{a\rho_s}$

3.2 GAM theory

The theoretical prediction of the GAMs was made by Winsor et al [4], however the interest on this mode was rekindled around 2005 because of the renovated interest in ZFs [15]. The flow structure for the ZFs GAM is symmetric with respect to the magnetic axis for modes with $m = n = 0$, the same happens for the stationary zonal flows, but for $m = 1$ the poloidal symmetry is broken because the pressure asymmetry due to the structure of the magnetic field in the toroidal configuration. Meanwhile for the local zonal flows there are no asymmetry.

Following [16] we will use the following equations

$$\frac{\partial}{\partial t}n + \nabla \cdot n\mathbf{V}_\perp + \nabla_\parallel nV_\parallel = S - \nabla \cdot \Gamma \quad (3.2.1)$$

$$nm_i \left(\frac{\partial}{\partial t}\mathbf{V} + \mathbf{V} \cdot \nabla \mathbf{V} \right) + \nabla p - \mathbf{J} \times \mathbf{B} = Sm_i \mathbf{V} \quad (3.2.2)$$

$$\nabla \cdot \mathbf{J} = 0 \quad (3.2.3)$$

$$\mathbf{E} + \mathbf{B} \times \mathbf{V} = 0 \quad (3.2.4)$$

They are the flux equation 3.2.1, the moment conservation equation 3.2.2, the charge neutrality condition, 3.2.3, and the Ohms law, 3.2.4. Here n is the density, $\mathbf{V}$ the velocity, $p = nT$ the preassure and Γ and S the particle flux and source. Introducing the expansion of the source and flux terms or of the function $F \equiv (S - \nabla \cdot \Gamma)/n_0$, we have

$$F = F_0(r) + F_1(r, \theta) + \tilde{F}(r, \theta, t) \quad (3.2.5)$$

where the first and second terms are the stationary part, which includes the poloidal asymmetry, and the third is the time-varying part that is the GAM associated term.

Using the linearization developed in [16] for the $E \times B$ velocity $\tilde{V}_{E \times B}$ in terms of the inverse aspect ratio $\epsilon = r/R$, we have

$$\frac{\partial}{\partial t} \tilde{N} - \frac{2}{R} \sin(\theta) \tilde{V}_{E \times B} + \nabla_{\parallel} \tilde{V}_{\parallel} = \tilde{F}(r, \theta, t) \quad (3.2.6)$$

$$\frac{\partial}{\partial t} \tilde{V}_{\parallel} + \frac{1}{r} \tilde{V}_{E \times B} \frac{\partial}{\partial \theta} \tilde{V}_{\parallel,1} + c_s^2 \nabla_{\parallel} \tilde{N}_{\parallel} - \mu_{\parallel} \nabla_{\perp}^2 \tilde{V}_{\parallel} = 0 \quad (3.2.7)$$

$$\frac{\partial}{\partial t} \tilde{V}_{E \times B} + \frac{2}{R} c_s^2 \oint \frac{d\theta}{2\pi} \sin(\theta) \tilde{N} = 0 \quad (3.2.8)$$

where $\tilde{N} = \tilde{n}/n_0$. For the GAM, the perturbation of the density has a dependence of θ of the form

$$\tilde{N}(r, \theta; t) = \tilde{N}(r; t) \sin(\theta).$$

Assuming the absence of $\tilde{F}(r, \theta, t)$, $\tilde{V}_{\parallel,1}$ and $\mu_{\parallel}$ and taking

$$\nabla_{\parallel} = \frac{1}{qR} \frac{\partial}{\partial \theta}$$

we have

$$i\omega \tilde{N} - \frac{2}{R} \sin(\theta) \tilde{V}_{E \times B} + \frac{1}{qR} \frac{\partial \tilde{V}_{\parallel}}{\partial \theta} = 0 \quad (3.2.9)$$

$$i\omega \tilde{V}_{\parallel} + \frac{c_s^2}{qR} \tilde{N} \cos(\theta) = 0 \quad (3.2.10)$$

$$j\omega \tilde{V}_{E \times B} + \frac{c_s^2}{R} \tilde{N} = 0 \quad (3.2.11)$$

and

$$\omega_{GAM} = \frac{c_s^2}{R^2} \left(2 + \frac{1}{q^2} \right) \approx \frac{\sqrt{2} c_s}{R_0} \quad (3.2.12)$$

where R_0 is the plasma major radius and c_s is the ion sound speed, given by

$$c_s = \sqrt{\frac{\gamma_i K T_i}{M}} \quad (3.2.13)$$

The safety factor at the plasma border can be calculated as

$$q_{edge} = \frac{5a^2 B_T}{R_0 I_p}, \quad (3.2.14)$$

where B_T is the toroidal magnetic field in Tesla, R_0 and a are the major and minor radii in meters, and I_p is the toroidal current in MA. In the case of the TCABR, $q \approx 3.5$, for $I_p = 80$ KA. The f_{GAM} calculated in the plasma border with $T_i \approx 30$ eV and $\gamma = 1.3$ is 22.5 kHz.

3.3 GAM measured characteristics

The detection of GAM and in general of ZF, is an experimental challenge because it requires the measurement of the plasma flow and of the electric field. There are basic two important class of measurements, the core and the edge measurements. The core measure are carried out with Heavy Ions Probes, that measure along chords in the plasma and give an information of the flow and temperature directly in the plasma. In the edge measurements the Langmuir probes are usually used due their simple construction and possibility to measure the signals in different positions of the plasma at the same time. This is the base for the turbulence measurements in the TCABR. As an example of detection of GAMs with Langmuir Probes, we have the JFT2M tokamak [17], where the GAM frequency is the range from 10kHz to 15kHz. For the HL-2A tokamak [18], [19], the configuration of the probes is show in figure 3.1, where $m \approx 0.9$ and $n \approx 0.2$ with $f_{GAM} \approx 6.8\text{kHz}$ and $f_{GAM} \approx 9.3\text{kHz}$.

Figure 3.1: Configuration of the Langmuir probes for the HL-2A tokamak[19].

For this experiments there where the symmetry between m and n has been detected. $f_{GAM} \approx 16\text{kHz}$.

The GAMs are usually located in the plasma edge, consistently with the theoretical predicted Landau damping of the form $\exp(-q^2)$, where $q(r)$ is a function that in general increases toward the core of the plasma column, that makes the GAMs be less damped toward the edge. As detected in the DIII-D [20], ASDEX-U [21], JFT-2M [22], TEXT-U [23] and T-10 [24]. The

result for the JFT-2M is show in Fig. 3.2(a)

Figure 3.2: GAM behavior as a function of the radio for the tokamaks a) DIII-D [20] and b) JFT- 2M[22].

The behavior of the GAM frequency as a function of the safety factor $q(r)$ is shown in Fig.3.2(a).

The dependence of frequency of GAM with the sound velocity c_s is shown in Fig.3.3 where the frequency is plotted as a function of the factor c_s/R . The data for several devices show a linear dependency of the frequency with the sound velocity .

Figure 3.3: GAM frequency as a function of the sound velocity c_s for several tokamaks [25].

Another important aspect of the GAMs is the sinusoidal dependence of the density with the poloidal angle, and with the fluctuating potential. The expression for this relation is present in equation

$$\frac{\tilde{n}}{n} = - \left(\sqrt{2} q_r \rho_s \frac{e\tilde{\phi}}{T_e} \right) \sin(\theta) \quad (3.3.1)$$

where θ is the poloidal angle, ϕ the fluctuating potential, q_r the radial wavenumber and ρ_S the Larmor radius.

Chapter 4

Data analysis

The analysis used in this work is based on the method presented in [6]. Following to this work several discharges of the TCABR have been analyzed, searching for the peak at $f \sim 40\text{kHz}$ which seems to be the frequency for GAM although the calculated frequency as was seen in section 3.2 it is for a temperature of 30eV 20~25 kHz, for the geometry and size of the TCABR tokamak. The discharges have been divided into three classes, based on the way to obtain the increment in the plasma density, which indicates the transition to the improved confinement mode. The following classification is used

- Without external perturbation : In these discharges no particular method was used; just an spontaneous increase in density occurred.
- Alfvén heated discharges: In this class RF power is applied by an external antenna. The energy of this signal dissipates in the form of electron energy due to conversion of the RF field into the kinetic Alfvén wave.
- Biasing discharges : In the biasing discharges, an electrode under electric potential is inserted into the plasma modifying the radial electric field.

In the first part we show the different configuration of the electrostatic probes for the discharges. Despite of not be found GAMs modes in the spontaneous increase and in Alfvén heating, are shown the results of analysis for this discharges. For the biasing class, several discharges are shown in which the suspected GAM peak appears.

4.1 Configuration of the electrostatic probes in the TCABR

The disposition in the TCABR tokamak of the electrostatic probes and the bias electrode (BE) are shown in figure 4.1. The BE is in the lower part of the plasma column and the electrostatic probes are in the equatorial plane of the plasma column.

Figure 4.1: Configuration of the probes LP5, LP6, RP and the bias electrode (BP) in the TCABR .

For the 14 pins probe (P14); the disposition of the pins and the direction in the plasma column are shown in figure 4.2. The distance between the pins is 0.5cm, giving a maximum toroidal distance of 3cm. Data from this probe were analyzed for discharges in the range from 24047 to 24145.

Figure 4.2: Schematic of the array of pins and direction for the P14.

he probe of 5 pins (LP5) is presented in figure 4.3. The probe has been used in all the discharges with bias and for the analyzed discharge with AW in the range 23988 to 24060.

4.1. CONFIGURATION OF THE ELECTROSTATIC PROBES IN THE TCABR29

Figure 4.3: Schematic of the array of pins and direction for the LP5. The pin in the square is dislocated 0.5cm in the radial direction.

The probe of 6 pins is show in figure 4.4. It has been used in the discharges with bias from 24122 to 24133.

Figure 4.4: Schematic of the array of pins and direction for the LP6. the pins in the square are dislocated 0.5cm in the radial direction.

In figure 4.5 is presented an schematic of the pins for the rack probe (RP). The numeration for the arrows of pins goes as a1 to a7, b1 to b7, and for the middle arrow from c1 to c6. The LP6 probe was used for the discharges with bias from 24122 to 24133 and from 27523 to 27535

Figure 4.5: Schematic of the array of pins and direction for the RP .

4.1.1 discharges with no external perturbation

There is a class of discharges where there is an increasing density without any external perturbation, not AW nor bias. In this class of discharges we have as example, the discharges 22094 and 22095.

The basic signals for the discharge 22095 are shown in figure 4.6, the density increase goes from $1.2 \times 10^{19} \text{m}^{-3}$ to $1.6 \times 10^{19} \text{m}^{-3}$, with also an increase of the plasma current before the rise in density. From the Mirnov coil there is growing MHD activity that has two steps, the first short from $t \approx 0.78 \text{ms}$ to $t \approx 0.81 \text{ms}$ then a three times increase of the magnitude of the oscillations from $t \approx 0.81 \text{ms}$ to $t \approx 0.95 \text{ms}$.

4.1. CONFIGURATION OF THE ELECTROSTATIC PROBES IN THE TCABR31

Figure 4.6: Basic signals for the discharge 22095. a) Plasma current, b) Loop voltage, c) soft x-ray for channels 5 and 6, d) Density for chord 2, e) Mirnov coil, f) Electrostatic probe.

The other discharge with similar characteristics is 22094 whose signals are shown in figure 4.7. The density increase goes from $1.0 \times 10^{19} \text{m}^{-3}$ to $1.4 \times 10^{19} \text{m}^{-3}$, with also an increase of the plasma current before the rise in density. In the Mirnov coils there are, as in the case of discharge 22095, two phases, but in this case the first one takes longer time and goes from 67ms to 78ms almost 10 times more than in 22095, and the second phase goes from 78ms to 104ms.

Figure 4.7: Basic signals for the discharge 22094. a) Plasma current, b) Loop voltage, c) soft x-ray for channels 5 and 6, d) Density for chord 2, e) Mirnov coil, f) Electrostatic probe.

The electrostatic probe configuration in this case was the one indicated in figure 4.2. Using the data from the probes, we proceed to calculate the temporal evolution of the correlation, shown in figure 4.8. There is a drop in the correlation when the density rises. This happens in the poloidal and toroidal directions, as seen for the pins 2 – 9 and 2 – 7, but the correlation is not affected in the toroidal direction for the pins as near as 5mm, as seen for the pins 2 – 3 and 3 – 4. The theory and experimental results shown that if a GAM mode occurs the coherence for long distance takes place because a global mode is generated. We assume an exponential decay of the cross-correlation of the form

$$C_{xy} \propto \exp\left(-\frac{d}{L}\right) \quad (4.1.1)$$

4.1. CONFIGURATION OF THE ELECTROSTATIC PROBES IN THE TCABR33

where L is the correlation length, d the distance between probes and C_{xy} the cross-correlation. We have a low correlation Length for these signals, as low as 1cm in the toroidal direction and 0.3cm in the poloidal direction.

Figure 4.8: Correlation signals for the pins of the electrostatic probe for the discharges 22094 and 22095, for the pins with respective distances 2 – 3@5mm-toroidal, 3–4@5mm-toroidal, 2–9@5mm-poloidal and 2–7@25mm-toroidal.

Carrying out the spectral analysis of the correlation, the results shown in figure 4.9 are obtained; they indicate that no enhancement of correlation between pins are present

Figure 4.9: Coherence analysis as a function of time for the pins of the electrostatic probe for the discharges a)22094 and b)22095 at the pins with its respective distances 2 – 9@5mm-poloidal and 2 – 7@25mm-toroidal.

In figure we can see harmonics, not so clear in 22095 but better in 22094, located at $f = 13\text{kHz}$, 26kHz and 39kHz . They are just the harmonics of the MHD activity as seen in Figs. 4.10a and 4.10b where the spectral density has been calculated for the data of the Mirnov coil.

Figure 4.10: Power spectral density analysis as a function of time for the Mirnov signal for discharges 22094 and 22095.

4.1. CONFIGURATION OF THE ELECTROSTATIC PROBES IN THE TCABR35

Now the $S(k, f)$ function is calculated for pairs of electrostatic probes. As seen in figure 4.11 when the density rises there is a concentration in the low wave number oscillations

Figure 4.11: $S(k, f)$ for discharge 22094 when there is, a) low density and, b) high density. The same analysis is done for the discharge 22095 when there is, c) low density and, d) high density. The analysis is performed between the pins 2 – 3@0.5cm-toroidal.

Furthermore, the spectra becomes more clearly dominated by the MHD harmonics as it is show in figure 4.12 for the two discharges. For high density there are the peaks of the MHD activity at $f \sim 14$ kHz and $f \sim 26$ kHz; these peaks fit well with those of the power spectra shown in figure 4.10a.

Figure 4.12: $S(f)$ for discharge 22094 when there is, a) low density and, b) high density. The same analysis is done for the discharge 22095 when there is, c) low density and, d) high density. The analysis is performed between the pins 2 – 3@0.5cm-toroidal.

For the others pins, we have a similar or more spread effect in the spectra for the values of $\sim 14\text{kHz}$ and $\sim 28\text{kHz}$, a similar results that show the MHD frequencies.

4.2 discharges heated with Alfvén waves

For Alfvén heated discharges, we could not detected any signal with indication of GAM. Eventhough we will make an analysis of three class of discharges that happened with this heating method. Three of them are the discharges 22047, 22121 and 24000. In this case, a Alfvén wave is excited in the plasma generating local heating. In this case, a Alfvén wave is excited in the plasma generating local heating. For the discharges considered, the RF pulse was applied at $t = 65\text{ms}$ with a power of 4KW. For the two first discharges the configuration of the pins for the electrostatic probe was the LP14, which is show in figure 4.2 and for discharge 24000 the configuration is that of the LP5 and RP probes, shown in figure 4.1. We have three situations

regarding the behavior of the MHD activity. In discharge 22047 the activity is high and does not change after the AW (Alfvén Wave); in 22121 the MHD activity is low and after the perturbation it continues low; for the discharge 24000 the MHD activity increases after the AW application. We see that the density also increases after the AW, probably indicating an increase in confinement. Considering first discharge 22047, the basic signals are shown in figure 4.13. For this discharge the Mirnov activity remains constant as seen directly from the Mirnov signal and from its spectral decomposition as a function of time. In the others signals we have that the plasma current decreases from 83KA to 73KA and the density increases from $2.3 \times 10^{19} \text{m}^{-3}$ to $2.9 \times 10^{19} \text{m}^{-3}$. The fluctuating potential instead changes and the oscillations that existed before become weaker.

Figure 4.13: Basic signals for the discharge 22047. a) Plasma current, b) Loop voltage, c) soft x-ray for channels 5 and 6, d) Density for chord 1, e) Mirnov coil, f) Electrostatic probe. The time for the Alfvén excitation is drawn as a black dotted line.

signal with a frequency of $f \sim 15\text{kHz}$ and its first harmonic at $f \sim 30\text{kHz}$ that comes from the MHD activity is observed. There is also present a spurious S-shaped harmonic that comes from the AW heating, as it will be shown.

Figure 4.14: Spectral analysis for the discharge 22047 where is shown an spurious S-shape signal and the harmonics of the MHD activity are observed.

The second class of discharge is shown in figure 4.15. In this case the plasma current increases from 91KA to 94KA, at the same time the density goes from $1.3 \times 10^{19} \text{m}^{-3}$ to $1.7 \times 10^{19} \text{m}^{-3}$. The MHD activity is low before the perturbation and remains low after that. Meanwhile the fluctuating potential as seen for the pin 5 remains the same after the application of the AW pulse.

Figure 4.15: Basic signals for the discharge 22121. a) Plasma current, b) Loop voltage, c) soft x-ray for channels 5 and 6, d) Density for chord 1, e) Mirnov coil, f) Electrostatic probe. The time of the Alfvén excitation is drawn as a dotted red line.

As seen in the spectrogram in figure 4.16, a signal with a frequency of $f \sim 15\text{kHz}$ and its first harmonic at $f \sim 30\text{kHz}$ that comes from the MHD activity is observed. As in the discharge 22047 there is a spurious S-shaped harmonic.

Figure 4.16: Autopower spectral density analysis for the Mirnov coil for the discharge 22121 where are shown, an spurious S-shape signal and the MHD activity at $f \sim 18$ kHz.

One important issue in the discharges with Alfvén heating is the observation of the S-shape noise signal, which appear in the band between 20kHz to 40kHz, as seen in figures 4.13 and 4.15. It is clear that this is an Alfvén signal as seen in the discharge 22086 show in figure 4.17. In this discharge a failure in plasma generation left just an Alfvén signal and the same S-shape signal appears. It is an important issue because the GAM are expected to appear in this band, but it can be seen that is no important signal in the fluctuating potential. This just happen in the magnetic probe, although in some electrostatic probes there is an influence of this spurious noise.

Figure 4.17: Spectral analysis for the discharge with disruption 22086, where it is shown an spurious signal from the Alfvén antenna

Now we consider discharge 24000, In this case the density goes from $1.1 \times 10^{19} \text{m}^{-3}$ to $1.3 \times 10^{19} \text{m}^{-3}$ during the heating via AW.

Figure 4.18: Basic signals for the discharge 2400. a) Plasma current, b) Loop voltage, c) soft x-ray for channels 5 and 6, d) Density for chord 2, e) Mirnov coil, f) Electrostatic probe. The time of the Alfvén excitation is drawn as a dotted red line.

In this case the MHD activity increases with the AW pulse, and a series of harmonics appears as seen in the spectral analysis of figure 4.19. However there is no S-shaped noise in this case.

Figure 4.19: Spectral analysis for the discharge 24000.

The signals of the electrostatic probes are not complete for the discharges 22047 and 22121 but it is possible to do an analysis for the more distant pins. On the other hand for the discharge 24000 we have just five pins but sufficient to do the analysis searching for the possibles GAM modes. For the discharge 22047 we have the more interesting behavior. There is a reduction in the correlation at the beginning of the Alfvén heating; the correlation increases at the same time of density increment it is present for long toroidal distances and low for short poloidal distances as happens with the pins 1 – 8 . This increment is coincident with a burst in the activity of the floating potential detected via electrostatic probe, as seen in figure 4.13 for the pin 5 of this discharge.

Figure 4.20: Correlation as a function of time for the discharge 22047 between the pins 1 – 2@0.5cm toroidal, 1 – 7@3cm toroidal, 1 – 8@3.5cm poloidal, 2 – 9@0.5cm poloidal and 2 – 6@2cm toroidal.

For the others tow discharges there is no appreciable change in the correlation between the pins, neither for short as for large distances, as seen in figures 4.21 and 4.22. for the discharge 22121 this low increment in correlation is coincident with the low MHD activity, for the discharge 24000 there is a saturation in the correlation.

Figure 4.21: Correlation as a function of time for the discharge 22121 between the pins 2 – 3@0.5cm toroidal, 2 – 7@3cm toroidal, 3 – 7@2cm poloidal, 2 – 7@2.5cm poloidal.

Figure 4.22: Correlation as a function of time for the discharge 24000 between the pins 1 – 2@0.4cm toroidal, 1 – 5@0.8cm toroidal and @0.5 radial, 2 – 5@0.4cm poloidal and @0.5cm radial.

In the case of the discharge 22047, where the reduction in the correlation is observed in figure 4.20; the same is also observed in the coherence as seen

in figure 4.23. It is interesting to note that just the MHD frequencies are correlated in a strong way as seen for the pins 2–6 at frequencies $f = 13\text{kHz}$, 26kHz and 39kHz at $t \sim 75\text{ms}$.

Figure 4.23: Coherence analysis as a function of time for the pins of the electrostatic probe for the discharge 22047 between the pins 1 – 2@0.5cm toroidal, 1 – 7@3cm toroidal, 1 – 8@3.5cm poloidal, 2 – 9@0.5cm poloidal and 2 – 6@2cm toroidal.

It is interesting to note that these harmonics have similar amplitudes in the spectra of the electrostatic probe meanwhile in the Mirnov probe, as show figure 4.24, the second and third harmonics are weak. Another point is, as had been noted before, that the S-shaped noise is just present in the spectra of the Mirnov signal.

Figure 4.24: Spectrum as a function of time for the Mirnov coil for the discharge 22047, showing the harmonics of the MHD activity at frequencies f 13kHz, f 26kHz and f 39kHz and a spurious S-shape noise of the Alfvén heating .

For the discharge 21121, the correlation spectra has no information, just random peaks. In his case there is no MHD activity and no other oscilations are detected.

Figure 4.25: Coherence analysis as a function of time for the pins of the electrostatic probe for the discharge 22121 between the pins 2 – 3@0.5cm toroidal, 2 – 7@3cm toroidal, 3 – 7@2cm poloidal, 2 – 6@2cm poloidal.

Now let us look at the spectral density for the correlation as a function of time. For the discharge 24000 there is a so high correlation that its not possible see the harmonics, but there is an interesting gap at $f \sim 25\text{kHz}$ at $t \sim 76\text{ms}$ where the correlation decreases.

Figure 4.26: Coherence analysis as a function of time for the pins of the electrostatic probe for the discharge 22400 between the pins 1 – 5@0.8cm toroidal and @0.5 radial, 2 – 5@0.4cm poloidal and @0.5cm radial.

Finally we have the function $S(k, f)$. This function has been calculated for the the discharges 22047, 22121, and 24000, from before the application of Alfvén power from 40ms to 60ms, and during the Alfvén heating 60ms to 90ms. The result of this calculation for the discharge 22047 is show in figure 4.27. There is a low frequency of $f \sim 5\text{kHz}$ and $k \sim 0\text{cm}^{-1}$, the other region that has oscillations in the $f \sim 15\text{kHz}$.

Figure 4.27: $S(k, f)$ function for discharge 22047 between the pins 2 – 6@2.0cm-toroidal. The times for the analysis are, before the heating, 40ms-60ms and, during the heating, 60ms-80ms .

When the density rises, the MHD and low frequency signal decreases

power. In fact as seen in figure 4.28, the MHD frequency goes from 3.8AU to 3.1AU and the low frequency goes from 3.4 to 3.1 . This low frequency and the first MHD harmonic are clear seen in figure 4.16 where the $S(f)$ spectra is shown.

Figure 4.28: $S(f)$ analysis for the discharge 22047 between the pins 2 – 7@3.5cm-toroidal.

The $S(k, f)$ function is shown in figure 4.29 for the discharge 22121 . A dispersion of the wave number that is the same for the times after and before the heating is observed. When the heating is present there is a distribution of the oscillations over similar band of frequencies. A more dense distribution is present for the case of the heating that in the no heating case.

Figure 4.29: $S(k, f)$ function for the discharge 22121 between the pins 2 – 7@3.5cm-toroidal. The times for the analysis are, before the heating, 40ms-60ms and, during the heating, 60ms-90ms.

When the $S(f)$ is calculated the result is show in figure 4.16. Is not clear any especial frequency when the Alfvén heating is performed. There is no other clear peaks and the S-shape spurious signal is not detected either in the electrostatic probes.

Figure 4.30: $S(f)$ analysis for the discharge 22121 between the pins 2 – 7@3.5cm-toroidal.

Before the heating there are no harmonics of the MHD activity. In this regime there is a low dispersion in wave number, in the band of $k \sim -20\text{cm}^{-1}$ to $k \sim 20\text{cm}^{-1}$. After the heating there are a several harmonics as seen in figure 4.19, that create an spread distribution near these frequencies in the band of $k \sim -150\text{cm}^{-1}$ to $k \sim 100\text{cm}^{-1}$. The spread is clear for the $S(k, f)$ function for the pins 2 – 5, as show in the analysis in figure 4.31

Figure 4.31: $S(k,f)$ analysis for the discharge 24000 between the pins 2 – 5@0.4cm-toroidal. The times for the analysis are, before the heating, 40ms-60ms and, during the heating, 60ms-80ms .

The presence of harmonics of the MHD activity are present via $S(f)$, where the sum over each value of k was done; this $S(f)$ spectrum is show in figure 4.32.

Figure 4.32: $S(f)$ analysis for the discharge 24000 between the pins 2 – 5@4mm-toroidal.

It is seen that discharges have a completely random distribution of the $S(f,k)$ spectra. There is not a special frequency of correlation near 40kHz that could be suspected to be a GAM.

4.3 discharges with biasing

Based on the results of Kuznetsov et. al. [6], an oscillation of $f \sim 40\text{KH}$ with symmetry for m and n is searched. Furthermore, the values of m and n have to be of the order of $m \sim 1 - 0$ and $n \sim 1 - 0$. It is possible calculate m and n as

$$m = k_{\theta} r_p \quad (4.3.1)$$

$$n = k_{\phi} (R + r_p) \quad (4.3.2)$$

where $r_p = 17.5\text{cm}$, and k_θ and k_ϕ are the poloidal and toroidal wave numbers. We indicate the list discharge of table 4.1. In the table it is indicated the behavior of the MHD activity when the electrode is switch on, as 'rise', when there is an increase of the MHD activity, and also 'equal' when the activity recorded for the Mirnov coils remains the same. The level of MHD is important because it is highly correlated with long correlation length in the poloidal and toroidal directions.

For the discharges 27523 – 27535 the bias electrode was 1cm inside the plasma, and voltages from 150V to 350V where applied. Probes LP5 and RP were used to collect the data. The probes were inserted in the plasma form 0cm (plasma boundary $r_p = 18\text{cm}$) to 1.0cm. For the discharges 24122 – 24133 the bias electrode was 1.5cm inside the plasma, and as used voltages of 350V, and the probes LP5, LP6 and RP were used to collect the data. The probes were inserted in the plasma form 0.5cm (plasma boundary) to 1.5cm. Next we will make an analysis of the discharges with frequency peak $f \sim 40\text{kHz}$ and one discharge without peak.

Table 4.1: List of discharges

discharge	E. Pos. (cm)	E. Pot. (V)	RP (cm)	LP5 (cm)	LP6 (cm)	MHD	f $\sim 40\text{kHz}$
24122	1.5	350	1.5	0.5	0.5	equal	YES
24124	1.5	350	1.5	0.1	0.5	rise	
24125	1.5	400	1.5	0.5	0.5	rise	
24126	1.5	350	1.5	1.0	1.0	equal	YES
24127	1.5	350	1.5	1.0	1.0	rise	YES
24128	1.5	350	1.5	1.0	1.0	rise	
24129	1.5	350	1.5	1.0	1.0	rise	
24130	1.5	350	1.5	1.0	1.0	rise	
24131	1.5	350	1.5	1.0	1.0	rise	YES
24132	1.5	350	1.5	1.0	1.0	rise	
24133	1.5	350	1.5	1.0	1.0	rise	
27523	1.0	150	0.0	0.0	—	equal	
27524	1.0	225	0.0	0.0	—	equal	
27525	1.0	300	0.0	0.0	—	equal	
27526	1.0	300	0.0	1.0	—	equal	
27527	1.0	300	0.0	0.5	—	equal	
27528	1.0	300	1.0	0.0	—	equal	
27529	1.0	300	0.5	1.0	—	equal	
27531	1.0	350	0.0	0.0	—	rise	
27532	1.0	350	0.0	1.0	—	rise	
27533	1.0	350	0.0	0.5	—	rise	
27534	1.0	350	1.0	0.0	—	rise	
27535	1.0	350	0.5	1.0	—	rise	

List of discharges for which the analysis was made, searching for the $f \sim 40\text{kHz}$. The position and potential of the electrode, the position of the probes, the level of MHD activity are listed and the presence of the frequency peak is indicated.

4.3.1 discharge 24126

For the discharge 24126 we have the basic signals in figure 4.33. After the bias, there is an increase in the density, from $1.0 \times 10^{19} \text{m}^{-3}$ to $1.8 \times 10^{19} \text{m}^{-3}$, the plasma current is stable and $I_p \sim 80 \text{KA}$. The Mirnov coil signal indicates an activity that decays before the bias, and when the bias is applied the activity remains the same.

Figure 4.33: Basic signals for the discharge 24126. a) Plasma current, b) Loop voltage, c) soft x-ray for channels 5 and 6, d) Density for chord 2, e) Mirnov coil, f) Electrostatic probe. The time of the Alfvén excitation is drawn as a dotted red line.

Next we calculate the correlation as a function of time. In this case an increase of the correlation happens when the bias is applied. The correlation

is observed for pins from distance 0.4cm, pins 5 – 7, to 219cm for pins 5 – 12. The correlation increases independently of the direction, poloidal or toroidal. Using equation 4.1.1 we have that the correlation length in the poloidal direction is $L \approx 13.3\text{cm}$ and in toroidal direction as long as $L \approx 239.0$ from the pins 5 – 12.

Figure 4.34: Correlation as a function of time for the discharge 24126 between the pins 3 – 5@54cm toroidal, 3 – 12@164cm toroidal, 5 – 12@219cm toroidal, 5 – 8@3 poloidal, 5 – 7@0.4cm poloidal and @0.5cm radial.

The coherence for this discharge is shown in figure 4.35. There is an increasing in the coherence when the bias is present, and this correlation is present for values of frequency $f \sim 14\text{kHz}$ that is present in the spectra from the Mirnov coil as seen in figure 4.36. Another feature appear at for $f \sim 40\text{kHz}$, and between the times $t \sim 75\text{ms}$ to $t \sim 85\text{ms}$. Another interesting fact is that the correlation is better at similar radial distance. For pins that are not at the same radial position (not shown) the correlation in the frequencies of interest is lower.

Figure 4.35: Coherence analysis as a function of time for the pins of the electrostatic probe for the discharge 24126 between the pins 3 – 5@54cm toroidal 3 – 12@164cm toroidal, 5 – 12@219cm toroidal, 5 – 8@3 poloidal, 8 – 10@0.4cm poloidal and @0.5cm radial.

Figure 4.36: Spectrum as a function of time for the Mirnov coil for the discharge 24126, showing the MHD activity at frequencies $f \sim 15\text{kHz}$ and no other signal.

The $S(k, f)$ function is calculated and presented in figure for the pins 5 – 7 which are separated 3cm in the poloidal direction, and those pins 5 – 12, separated 219cm. The $S(k, f)$ function is calculated before and during the bias application. The peak of $k \sim 40\text{kHz}$ is observed just for the biasing mode for the two pins pairs as seen too in figure 4.38 where

de density spectra is calculated for an interval before bias and the interval durin the bias. Also it is observed an MHD oscillation of $f \sim 15\text{kHz}$ and a low frequency peak of $f \sim 5\text{kHz}$.

Figure 4.37: $S(k, f)$ function for the discharge 24126 between the pins 5 – 7@0.4cm in the poloidal direction 5 – 12@219cm. The times for the analysis are, before the bias, 55ms-75ms and, during heating, 75ms-90ms.

The poloidal and toroidal wave numbers of this frequency, as expected for a GAM, are low, $k_\theta \sim 0.05\text{cm}^{-1}$ and $k_\phi \sim 0.005\text{cm}^{-1}$. Calculating m and n using the values of the wave numbers in equation 4.3.1 and 4.3.2, we have $m \sim 0.8$ and $n \sim 0.1$.

Figure 4.38: $S(f)$ analysis for the discharge 24126 between the pins 5 – 7@0.4cm-poloidal a) before bias and b)during bias. And for the pins 5 – 12@219cm-toroidal c)before bias and d)during bias.

4.3.2 discharge 24127

For this discharge the increase of the density goes from $n \sim 1.1 \times 10^{19} \text{m}^{-3}$ to $n \sim 1.8 \times 10^{19} \text{m}^{-3}$, a relative increase of 63% in density. The Mirnov coil signal show an increase in the MHD activity that grows three times when the bias is applied. For the fluctuating potential, there is an increase during the bias application but this increase is larger for the inner pins (1.5 inside plasma) than in the outer pins.

Figure 4.39: Basic signals for the discharge 24127. a) Plasma current, b) Loop voltage, c) soft x-ray for channels 5 and 6, d) Density for chord 2, e) Mirnov coil, f) Electrostatic probe. The time of the Alfvén excitation is drawn as a dotted red line.

The correlation for the signals of electrostatic probe pins with different distances between them is shown in figure 4.40. As in the previous discharge the correlation increases for all distance and directions, as it can be seen by the correlation between pins 3 – 5, separated 54cm in the toroidal direction. In this case the correlation distance has a value $L \approx 151\text{cm}$. The same happens for pins 5 – 12, separated 219cm; for these pins the correlation distance is $L \approx 45\text{cm}$. For the pins 5 – 8 separated 3cm in the poloidal direction, the correlation distance is $L \approx 151\text{cm}$.

Figure 4.40: Correlation as a function of time for the discharge 24127 between the pins 3–5@54cm toroidal, 3–12@164cm toroidal, 5–12@219cm toroidal, 5–8@3 poloidal, 5–7@0.4cm poloidal and @0.5cm radial.

The coherence in this discharge as seen in figure 4.40, presents an increase in the correlation for the frequencies; a low frequency $f_l \sim 1\text{kHz}$, an MHD oscillation at $f_{MHD} \sim 15\text{kHz}$ that appears in the Mirnov signal, and a region near the $f \sim 40\text{kHz}$. All these increases happen approximately between $t_1 \sim 75\text{ms}$ and $t_2 \sim 85\text{ms}$, and they are valid for near pins, as 5–8 as well as for long distance pins as 5–12.

Figure 4.41: Coherence analysis as a function of time for the pins of the electrostatic probe for the discharge 24127 between the pins 3 – 13@164cm toroidal, 6 – 12@219cm toroidal, 5 – 8@3 poloidal, 9 – 12@219cm toroidal.

The Mirnov coil signals, shown in figure 4.42, do not show activity in the range $f \sim 40\text{kHz}$ for this discharge, this activity is just registered by the electrostatic probes.

Figure 4.42: Spectrum as a function of time for the Mirnov coil for the discharge 24127, showing the MHD activity at frequencies $f \sim 15\text{kHz}$ and no other signal.

The $S(k, f)$ function is shown in figure 4.43d. It shows a similar behav-

ior with that of the discharge 24126. Before the bias, there is a very low frequency and a MHD activity. During the bias, there is an extra feature around $f \sim 40\text{kHz}$. This happens for several combinations of pins and is clear in the spectral density as seen in figure 4.44. In this case are shown the effect for 5 – 12 separated in the toroidal direction and 5 – 7. The values of m and n are calculated using $k_\theta = 0.05\text{cm}^{-1}$ and $k_\phi = 0.005\text{cm}^{-1}$ are $m \sim 0.8$ and $n \sim 0.1$. Then we have again an oscillation frequency that does not correspond to MHD oscillations, and with symmetry in the poloidal and toroidal directions.

Figure 4.43: $S(k, f)$ function for the discharge 24127 between the pins 5 – 7@0.4cm and 5 – 12@219cm in the poloidal direction. The times for the analysis are, before the bias, 55ms-75ms and, during heating, 75ms-90ms.

Figure 4.44: $S(f)$ analysis for the discharge 24127 between the pins 5 – 7@0.4cm-poloidal a) before bias and b)during bias. And for the pins 6 – 12@219cm-toroidal c)before bias and d)during bias.

4.3.3 discharge 24131

The basic signals for this discharge are presented in figure 4.45 . The density in this case goes from $n_e \approx 1.3 \times 10^{19} \text{m}^{-3}$ to $n_e \approx 1.8 \times 10^{19} \text{m}^{-3}$, a relative increase of $\sim 42\%$ when the bias is on. The MHD activity increases as four times and decays during the presence of the bias.

Figure 4.45: Basic signals for the discharge 24131. a) Plasma current, b) Loop voltage, c) soft x-ray for channels 5 and 6, d) Density for chord 2, e) Mirnov coil, f) Electrostatic probe. The time of the Alfvén excitation is drawn as a dotted red line.

The correlation as a function of time is presented in figure 4.46, the coherence rises clearly for pins separated by 54cm; this is the case for pins 3 – 5. For pins separated larger distances the correlation is smaller than in the previous discharges. There are three peaks at $t_a \approx 79$ ms, $t_b \approx 82$ ms and $t_c \approx 86$ ms. These peaks correspond to the maximum in the correlation for pins at lower distances. Then the increase in correlation is a general feature for all pins.

Figure 4.46: Correlation as a function of time for the discharge 24131 between the pins 3–5@54cm toroidal, 3–12@164cm toroidal, 5–12@219cm toroidal, 5–8@3 poloidal, 5–7@0.4cm poloidal and @0.5cm radial.

The coherence as a function of time is calculated in figure 4.47, we can see that the coherence has a peak at $f \sim 40\text{kHz}$. The peak happens when the bias is applied, at time $t \sim 78\text{ms}$. The increase of the coherence is clear for distant pins as 3–12 and 5–12, and yet when the correlation for the MHD frequency of $f \sim 13\text{kHz}$ is not present, the coherence at $f \sim 40$ is visible.

Figure 4.47: Coherence analysis as a function of time for the pins of the electrostatic probe for the discharge 24131 between the pins 3–5@54cm toroidal, 3–12@164cm toroidal, 5–12@219 toroidal, and 5–8@3cm poloidal.

In contrast with the spectra of the correlation spectra for the electrostatic probes, in figure 4.48 the Mirnov signal not show an strong frequency component near the 40kHz. The Mirnov activity is for the MHD oscillation at 17kHz and it first harmonic at 34kHz.

Figure 4.48: Spectrum as a function of time for the Mirnov coil signal the discharge 24131, showing the MHD activity at frequencies f 15kHz and a tenuous harmonic at 30kHz .

The $S(k, f)$ analysis is presented in figure 4.49 for times from 60ms to 75ms, and for the time before bias, from 75ms to 90ms. There are four peaks when the bias is on, the lower frequency at $f \sim 2$ kHz, the MHD frequency $f \sim 13$ kHz and its first harmonic at $f \sim 26$ kHz, and a oscillation at $f \sim 40$ kHz. The oscillation of 40kHz is clearly observed in the figure 4.50 where the spectral density is shown. For the suspected GAM frequency the values for m and n are calculated, using $k_\theta = 0.05\text{cm}^{-1}$ and $k_\phi = 0.013\text{cm}^{-1}$ are $m \sim 0.8$ and $n \sim 0.2$. Then we have again an oscillation of frequency that does not correspond with the MHD oscillations, and with symmetry in the poloidal and toroidal directions.

Figure 4.49: $S(k, f)$ function for the discharge 24131 between the pins 5 – 7@0.4cm in the poloidal direction 6 – 12@219cm. The times for the analysis are, before the bias 60ms-75ms and during heating 75ms-90ms.

Figure 4.50: $S(f)$ analysis for the discharge 24131 between the pins 5 – 7@0.4cm-poloidal a) before bias and b)during bias. And for the pins 6 – 12@219cm-toroidal c)before bias and d)during bias.

4.3.4 discharge 24122

The basic signals for this discharge are presented in figure 4.51. The density in this case goes from $n_e \approx 1.0 \times 10^{19} \text{m}^{-3}$ to $n_e \approx 1.7 \times 10^{19} \text{m}^{-3}$ a relative increase of $\sim 51\%$ when the bias is on. The MHD activity does not change during bias.

Figure 4.51: Basic signals for the discharge 24122. a) Plasma current, b) Loop voltage, c) soft x-ray for channels 5 and 6, d) Density for chord 2, e) Mirnov coil, f) Electrostatic probe. The time of the Alfvén excitation is drawn as a dotted red line.

The correlation as a function of time is presented in figure 4.52. The correlation increases for distances between pins as long as 219cm during the bias, in both poloidal and toroidal directions. In the toroidal direction it increases from $C \approx 0.05$ to $C \approx 0.$. For the probes at distance of 54cm the correlation length goes from $L \approx 18\text{cm}$ to $L \approx 152\text{cm}$. In the poloidal distance the same increase happens for probes at 3cm and the correlation length goes from $L \approx 1\text{cm}$ to $L \approx 6\text{cm}$. For the more distant probes in the toroidal direction, 164cm and 219cm, the increase goes from $C \approx 0.05$ to $C \approx 0.4$, increasing the correlation length from 54cm to 178cm and from

73cm to 239cm, respectively.

Figure 4.52: Correlation as a function of time for the discharge 24122 between the pins 3–5@54cm toroidal, 3–12@164cm toroidal, 5–12@219cm toroidal, 5–8@3 poloidal, 5–7@0.4cm poloidal.

The coherence as a function of frequency and time is calculated in figure 4.53. The coherence is strong for the MHD frequency, and in the region between 30kHz and 40kHz the correlation increases. It happens for the combination of pins that are at distances form 54cm, 164cm and 219cm.

Figure 4.53: Coherence analysis as a function of time for the pins of the electrostatic probe for the discharge 24131 between the pins 3 – 5@54cm toroidal, 3 – 13@164cm toroidal, 5 – 13@219 toroidal, and 5 – 8@3cm poloidal.

Figure 4.54: Spectrum as a function of time for the Mirnov coil for the discharge 24122, showing the MHD activity at frequencies f 16kHz and the absence of any other type of oscillations in the time of bias application .

The $S(k, f)$ function is presented in figure 4.55. The peaks that appears in the graph correspond to MHD frequency at $f \sim 15\text{kHz}$ and there is a peak in the $f \sim 35\text{kHz}$ which is strong for short and long distances and does not correspond to an harmonic of the MHD activity. This oscillation is seen more clear for the spectral density as seen in figure 4.56 The oscillation of

$f \sim 35\text{kHz}$ has k_θ and k_φ near to zero.

Figure 4.55: $S(k, f)$ function for the discharge 24122 between the pins 5 – 7@0.4cm in the poloidal direction 5 – 13@219cm. The times for the analysis are, before the bias 60ms-80ms and during heating 80ms-100ms.

Figure 4.56: $S(f)$ analysis for the discharge 24122 between the pins 5 – 7@0.4cm-poloidal a) before bias and b)during bias. And for the pins 5 – 13@219cm-toroidal c)before bias and d)during bias.

4.3.5 discharge 27527

The basic signal for this discharge are shown in figure 4.57 . The conditions in this discharge has the following differences with the discharge 22146; the deep of the bias electrode was 0.5cm lower ($r_B = 18.5\text{cm}$) and the bias potential 50V lower ($V_B = 300\text{V}$), but the current was the same, 150A. The conditions for this discharge are similar for the 275xx discharges as show in table 4.1 . As seen in the signals, the plasma conditions were similar.

The density in this case goes from $n_e \approx 1.0 \times 10^{19}\text{m}^{-3}$ to $n_e \approx 1.9 \times 10^{19}\text{m}^{-3}$ a relative increase of $\sim 90\%$ a rise that is superior for this discharges with with respect to the discharges that have the suspected GAM mode. The x-ray for the central channel has an increase as the fluctuating potential. The plasma current remains constant in the $I_p \approx 80\text{KA}$.

Figure 4.57: Basic signals for the discharge 27527. a) Plasma current, b) Loop voltage, c) soft x-ray for channels 8 and 12, d) Density for chord 2, e) Mirnov coil, f) Electrostatic probe. The time of the Alfvén excitation is drawn as a dotted red line.

There is an increase in the amplitude of MHD activity during the presence of the bias as seen in figure 4.58, but it is not observed the presence of harmonics or any other frequency of oscillation.

Figure 4.58: Spectrum as a function of time for the Mirnov coil for the discharge 27527, showing the MHD activity at frequencies f 16kHz and the absence of any other type of oscillations in the time of bias application.

The correlation as a function of time is presented in figure 4.59. The correlation increases for short distances, between pins (0.4cm) but it is low, of the order of 0.05, for long distances between probes, in this case 164cm. The value of the correlation for the long distant probes is low compared with the correlation peak for the discharges with the $f \sim 40$ kHz.

Figure 4.59: Correlation as a function of time for the discharge 27527 between the pins 1 – 2@0.4cm poloidal, 1 – 3@0.8cm poloidal, 1 – 6@164cm toroidal and 1 – 13@164 toroidal.

The coherence as a function of time is shown in figure 4.60. The coherence has no presence of MHD activity but neither of another type of phenomena, just the low frequency signal $f < 1$ kHz. It is interesting because the incre-

ment in the density is as was discussed, approximately 90%.

Figure 4.60: Coherence analysis as a function of time for the pins of the electrostatic probe for the discharge 27527 between the pins 1 – 2@0.4cm poloidal, 1–3@0.8cm poloidal, 1–6@164cm toroidal and 1–13@164 toroidal.

The $S(k, f)$ analysis is presented in figure 4.61. The peaks that appear in the graph correspond to MHD frequency and its first harmonic, and does not exist a signal at $f \sim 40\text{kHz}$ that show the presence of the presumed GAM. The absence is more clear in figure 4.62, where the spectral density has been calculated.

Figure 4.61: $S(k, f)$ function for the discharge 27527 between the pins 1 – 2@0.4cm in the poloidal direction 1–6@164cm in the toroidal direction. The times for the analysis are, before the bias, 40ms-60ms and, during heating, 60ms-80ms.

Figure 4.62: $S(f)$ analysis for the discharge 27527 between the pins 1 – 2@0.4cm-poloidal a) before bias and b) during bias. And for the pins 1 – 6@160cm-toroidal c) before bias and d) during bias.

Chapter 5

Conclusions and perspectives

This work reports the analysis of TCABR discharges with the plasma density increasing from three different reasons. These ways were, the spontaneous increment, the increment by mean of Alfvén waves and the increase in density caused by bias. The performed analyses were the correlation, auto power spectra, coherence and power spectral density for wave number and frequency. These methods were applied for the electrostatic probes signals. For the signals of Mirnov coils the auto-power spectra was used.

For the spontaneous increment of density the result is negative for GAMs: the analysis shows just a little increase in the density and in the correlation. The increment in the correlation was due to a great MHD activity in the plasma column.

As shown in the analysis of the discharges heated by Alfvén waves, presented in section 4.2 there is not a clear presence of the GAM modes in the band expected for the dimensions and characteristics of operation of the TCABR. A possible explanation of this observation is that the Alfvén heating could send impurities into the plasma, deteriorating the plasma confinement. Another explanation is that the discharges was done with an initial density too high and then the confinement was not improved at the range of the conditions for the formation of GAMs. The presence of long distant correlation in the plasma is not a uniquely indicator of the GAM presence, although the presence of this modes generate a notable increase in the correlation for long distant points. In the case of the Alfvén heated plasma this increment in correlation is due to MHD activity.

For the bias discharges we have reproductively observed a peak of $f \sim 40\text{KHz}$, for example for discharges 24122, 24126, 24127, 24131, those discharges are presented in section 4.3. In the case of the bias discharges the correlation was increased by a factor 8 even for probes toroidally separated by 164cm or 219cm each other. This increment in the correlation was not due to MHD activity that remains in low levels after the bias application. The conditions for this discharges are similar in bias voltage, current of bias

and electrode position into plasma, as seen in the table 4.1, Meanwhile for the discharges between 27523 to 27535 where no GAMs were detected, the condition that changed was the deep of the electrode into the plasma, in this case a difference of 0.5cm although the presence of impurities in the electrode for the second group of discharges could be a reason for not GAMs occurrence. As seen for the coherence as a function of time for the discharges with the suspected GAM mode, the presence of the increase in the correlation for the band near the 40KHz is present at the beginning of the application of bias. In the case of the discharges when the bias is on in 75ms the activity goes approximately from this initial time to 85ms, and in the case of the discharge with bias on at 80ms, the activity goes to a time of approximately 90ms. This indicate a formation of GAM just when the density increases. The frequency of the GAM mode has not a perceptible variation of the frequency as a function of the radius. The pins for the discharges has a difference in distance in the radial direction of 1cm.

Further works on GAMs in TCABR could try to verify the poloidal distribution of the GAM-induced density oscillations, which fluctuations are expected to be of the form proportional to $\sin(\theta)$ as seen in 3.3.1. In order to do that, it will be necessary to construct a poloidal array of Langmuir probes and set these probes to measure the ion saturation current. As seen in the expression of the density fluctuations of the GAM oscillations, it is necessary to improve the measure of the local temperature with Langmuir probes [26]. It will help comparisons between experimental data and theoretical predictions.

Measurements of local temperature fluctuations also allow to improve the characterization of the plasma edge turbulence in TCABR and its modification by the formation of transport barriers by edge biasing [27] and by the growth of MHD activity [28]. Two important parameters to characterize the edge turbulence are the turbulent-drive particle flux, $Q = \langle \tilde{n} \tilde{v}_r \rangle$, and the turbulent-drive energy flux, $\tau = \langle \tilde{n} T_e \tilde{v}_r \rangle$, where $\tilde{v}_r$ is the fluctuation of the radial velocity due to the $\tilde{E}_\theta \times B_T$ drift, with $\tilde{E}_\theta$ estimated from the poloidal variation of the plasma potential, ϕ measured by two near probes. Previous works in TCABR did not measure the local temperature fluctuations and could not determine the energy flux. Moreover, by simultaneously measuring the local temperature and its fluctuations, it is possible to avoid some usual approximations used to compute the particle flux: $\tilde{n} \propto \tilde{I}_{Sat}$ and $\tilde{V}_f \propto \tilde{\phi}$.

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