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Ministère de l'Enseignement Supérieur et de la Recherche Scientifique
Université de Béchar
Faculté des Sciences et de technologie
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HABILITATION UNIVERSITAIRE

Présentée pour l'obtention le grade de

Maître de Conférences Classe A

Spécialité : Physique Electronique et Modélisation

Travaux de Recherche après et avant Thèse (CV détaillé)

Présenté par : *Melle SABRI Naima Ghoutia*
Doctorat en sciences physiques de l'université de Tlemcen. Algérie

Année universitaire : 2011/2012

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1. STUDY OF ENERGY TRANSFER BY ELECTRON CYCLOTRON RESONANCE IN TOKAMAK PLASMA, 2011 PUBLISHED BY ELSEVIER LTD. *ENERGY PROCEDIA 6 (2011) 194–201P.194-201.*

I.1.2. PUBLICATIONS NATIONALES

1. " STUDY OF ALFVEN WAVES IN COLLISIONNELS AND COLLISIONLESS PLASMAS " JOURNAL OF SCIENTIFC RESEARCH NUMBER : 0, ISSUE 1 (2010), P.207-213.

I.1.3. COMMUNICATIONS INTERNATIONALES

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2. "Comparative study between kinetic and fluid models at the core and the edge of the tokamak plasma**».** Tu-MRS **(**TUNISIAN MATERIALS RESEARCH SOCIETY**),** Matériaux 2010, 5-6 et 7 Novembre 2010 à Mahdia, Tunisie.
3. « Study Of Electron Cyclotron Absorption In Tokamak Plasma Using Kinetic Model", Le Séminaire International Sur La Physique Des Plasmas, Sipp'2011, Ouargla, Algérie – Du 13 Au 17 Février 2011.
4. "Production of thermonuclear energy by plasma additional heating systems with electron cyclotron and Alfven waves in tokamak machine", Sharjah International Conference on Nuclear and Renewable Energy- SHJ-NRE11 "*Energies for the 21st Century*". April 3-5, 2 011, Sharjah, United Emirat.
5. "Study of energy transfer by electron cyclotron resonance in tokamak plasma" MEDGREEN 2011-LB Conference, Impact of Integrated Clean Energy on the Future of the Mediterranean Environment. 14-16 April 2011, Beirut- Lebanon.
6. "Study of Radiometry of ECE in Tkamak Plasma, The Eight IEE and IFIP International Conference on Wireless and Optical Communications Networks, WOCN 2011, May 24th-25th, 2011 Paris (France). **(Acceptée).**
7. "18 international colloquium on plasma process (CIP 2011)", July 4th-8th, 2011, Nante, France (**Acceptée**).

I.1.4. COMMUNICATIONS NATIONALES

1. "Study of Alfvèn Waves Properties and its Role in Additional Heating of Tokamak Plasma", La 7ème Conférence Sur Le Génie Electrique (CGE'07), 12-13 Avril 2011, Ecole Militaire Polytechnique- EMP, Bordj El Bahri, Alger, Algérie.
2. « Study Of The Ion cyclotron Resonance Heating In Tokamak Plasma », 4ième conférence national sur les rayonnements et leurs applications, CNA, USTHB Alger, 25-27 Octobre 2011.

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Study of energy transfer by electron cyclotron resonance in tokamak plasma

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Abstract

A theoretical study of energy transfer by electron cyclotron resonance to tokamak plasma is presented. Then the predictions of linear theory including relativistic effects on the wave absorption are examined. Electron-cyclotron (EC) absorption in tokamak plasma is based on interaction between wave and electron cyclotron movement when the electron passes through a layer of resonance at a fixed frequency which depends on the magnetic field. This technique is the principle of additional heating (ECRH) and the generation of non-inductive current drive (ECCD) in modern fusion devices. The power absorbed depends on the optical depth which in turn depends on coefficient of absorption and the order of the excited harmonic for O-mode or X-mode.

Keywords: Energy; transfer; electron cyclotron; resonance; tokamak; heating.

1. Introduction

The need to have a secure and clean supply of energy for our growing industrial civilization has led us to search for alternative supplies of energy. Energy produced from thermonuclear fusion reactions had been known for some decades in the sun and stars, is likely safe and don’t produces greenhouse gas emissions and its radioactive wastes is less expensive to manage.
These reactions require special conditions of temperature (100 million degrees) and pressure. In this case, the more promoter configuration to realize them is tokamak which is a machine governed by Lawson

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criterion [1], $nTt_E \geq 5.10^{21}\ m^{-3} keVs$ and to achieve these high temperatures, it is necessary to heat the plasma. The ohmic regime is a primary natural mechanism of heating. Unfortunately, this effect is proportional to the resistance of the plasma which tends to collapse when the temperature increases. We therefore use additional heating systems. Radio-frequency heating is one of important of these systems. This phenomenon occurs if the waves have a particular frequency (the same as charged particles frequency), their energy can be transferred to the charged particles in the plasma, which in turn collide with other plasma particles, thus increasing the temperature of the bulk plasma.

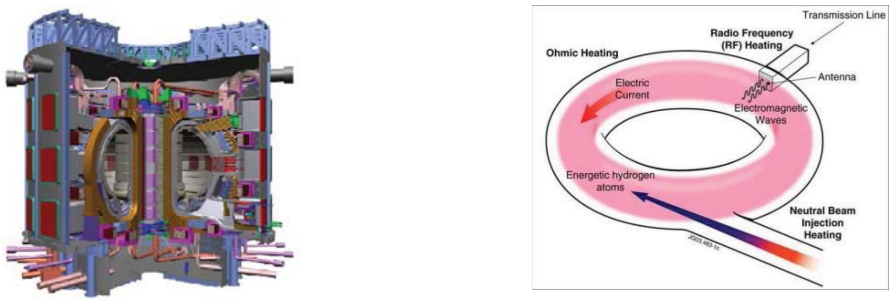


Fig. 1. (a) Tokamak machine- ITER; (b) Heating methods

According the frequency range, there are three main types of radio-frequency heating [2]:

- The heating at the ion cyclotron frequency (ICF): a few tens of megahertz (MHz).
- The heating at hybrid frequency: a few gigahertzes (GHz).
- The heating at the electron cyclotron frequency (ECF): the hundreds of (GHz).

2. Electron Cyclotron Frequency

If the particle is an electron $q = -e$; its frequency of rotation ω_{ce} is called the electron cyclotron frequency given by $\omega_{ce} = 2\pi f_c = \frac{e\,B}{\gamma m_e}$. Where $\gamma = 1/\sqrt{1 - (\mathrm{v/c})^2}$ [3], the relativistic Lorentz factor, $\gamma = 1$ for a non-relativistic plasma (v << c).

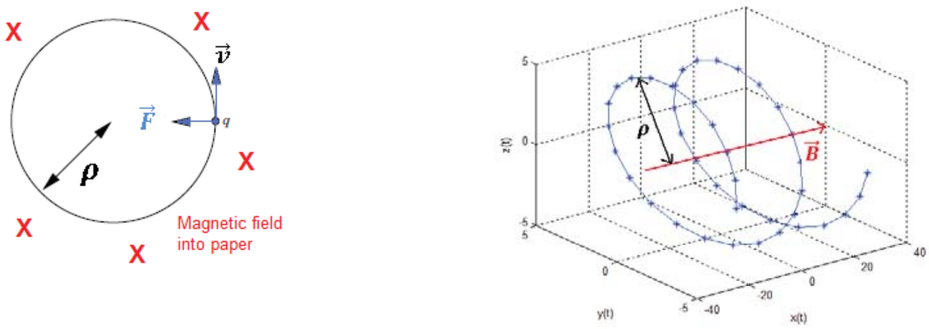


Fig. 2. (a) Effect of magnetic field on charged particle (b) spiral trajectory of charged particle

The radius of the circular rotation is called Larmor radius given by

$$\rho = \frac{\gamma m_e v_\perp}{e\,B} \quad (1)$$

With $v_\perp$ is the component of velocity perpendicular to $\vec{B}$. Since the gyration of electrons is periodic, it emits radiation in a series of harmonics

$$\omega_{cen} = \frac{n\omega_{ce}}{1-\frac{v_{II}}{c}\cos\theta} \quad (2)$$

Where n is the number of harmonics, v_{II} is the velocity component parallel to $\vec{B}$: The angle θ between the line of sight and the magnetic field $\vec{B}$. For $\theta \neq 90°$, we observe an oblique electron cyclotron emission. If $\theta = 90°$; equation (2) can be rewritten as $\omega_{cen} = n\omega_{ce} = 2\pi n f_c$.

2. Propagation and Dispersion Relation

To describe the propagation of electron cyclotron waves in plasma is generally used the cold plasma approximation [4]. In this approximation the plasma pressure is assumed very small compared to the magnetic pressure $\beta \ll 1$. In this case the thermal motion of electrons may be negligible in terms of oscillations of the wave $v_\varphi \gg v_{th}$ where v_φ is the wave phase velocity and v_{th} is a thermal velocity of electrons and the Larmor radius is small compared to the wavelength [5]. Considering plane wave solutions of Maxwell's equations, such as fluctuating quantities vary as $exp\,(i\,(\vec{\boldsymbol{k}}.\vec{\boldsymbol{r}} - \omega t))$. In Fourier space, we can find a wave equation of the form [6]:

$$k^2\vec{\boldsymbol{E}} - \vec{\boldsymbol{k}}(\vec{\boldsymbol{k}}\vec{\boldsymbol{E}}) - \left(\frac{\omega^2}{c^2}\right)\vec{\boldsymbol{D}} = 0 \quad (3)$$

Where $\vec{\boldsymbol{k}}$ is the wave vector, $\vec{\boldsymbol{D}} = \overline{\overline{K}}\vec{\boldsymbol{E}}$ is the electrical induction vector, $\overline{\overline{\boldsymbol{K}}}$ is the dielectric tensor [1] [4], [7], $\vec{\boldsymbol{E}}$ is the vector of wave electric field. If the refractive index is written as $\vec{\boldsymbol{N}} = \frac{\omega}{c}\vec{\boldsymbol{k}}$, the equation (3) can conduct to resolving the dispersion equation which may take the form :

$$AN^4 + BN^2 + C = 0 \quad (4)$$

With $A = Ssin^2\theta + Pcos^2\theta$, $B = RLsin^2\theta + PS(1 + cos^2\theta)$ and $C = PRL$. In the case of perpendicular propagation to magnetic field ($N_{II} = 0$). We obtain two solutions of equation (4) for the perpendicular refractive index, which can be written:

$$N_O^2 = P = 1 - \frac{\omega_p^2}{\omega^2}, \quad (5)$$

$$N_X^2 = \frac{S^2 - D^2}{S} = 1 - \frac{\omega_{pe}^2}{\omega^2}\frac{(\omega^2 - \omega_{pe}^2)}{(\omega^2 - \omega_{pe}^2 - \omega_{ce}^2)} \quad (6)$$

These transverse electromagnetic solutions are well known by the names of ordinary mode (O-mode) and extraordinary mode (X mode) [8]. The first mode does not have any resonance and propagate for $\omega > \omega_{pe}$ because of the cut-off and the second one has two cut-offs and two resonances. According to the phase velocity ω/k, it decomposes in fast (F) and slow (S) as shown in Fig 3 and in Fig 4.

The two branches of propagation (ordinary and extraordinary) appear and we can see that the ordinary mode propagates for frequencies such that $\omega > \omega_{pe}$. The extraordinary mode is propagated for $\omega_L < \omega < \omega_{uh}$, evanescent for $\omega_{uh} < \omega < \omega_R$. It becomes propagative when $\omega > \omega_R$. With ω_R, ω_L are the cutoff frequencies of the X mode, called right and left modes, defined by:

$$\omega_{R,L} = \frac{1}{2}\left[\mp\omega_c + \left(\omega_c^2 + 4\omega_p^2\right)^{1/2}\right] \quad (7)$$

The X mode has a cold resonance ($N_\perp \to \infty$), given by:

$$\omega_{uh} = \sqrt{\omega_c^2 + \omega_p^2} \quad (8)$$

This resonance is called upper hybrid (UH) is not available if $\omega > \omega_c$. There is also a lower hybrid resonance [9], it is well below the electron cyclotron frequency domain and therefore not interfere here.

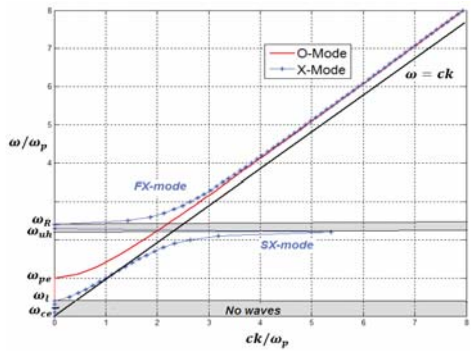


Fig. 3. the dispersion diagram

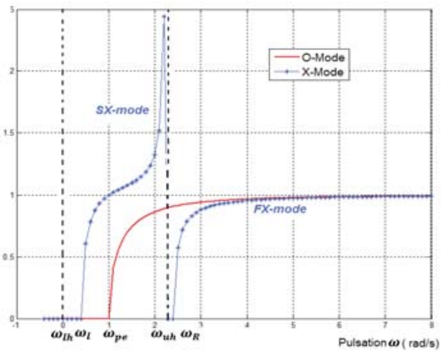


Fig. 4. $N^2 = f(\omega)$ for perpendicular propagation

3. Energy Transfer

The mechanism of wave energy transfer by absorption is schematized on the Fig.5. In a tokamak, the production of an electromagnetic power is usually made by gyrotrons for ECRH and transported to the plasma by transmission lines. What causes an excitation of a plasma wave at the edge. This wave traveling toward the center by carrying the power and in a resonance layer near of $\omega = \omega_c$, it will be absorbed by transferring its energy to the resonant electrons which in turn collide with other plasma electrons. Finally these particles thermalize, thus increasing the temperature of the bulk plasma (see Fig.5).

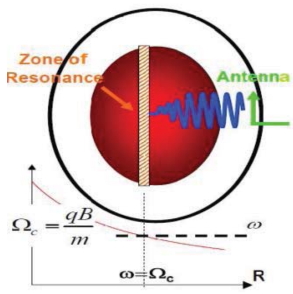


Fig.5. Principle of ECR heating

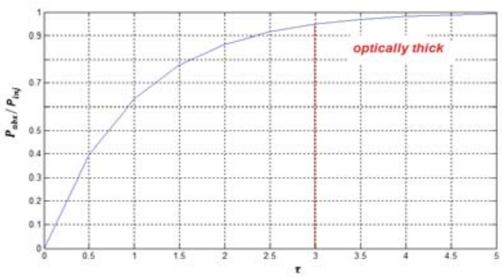


Fig.6. Fraction of power absorbed as a function of τ, ($\tau > 3$) [2].

3.1. Absorption of Electron Cyclotron Wave in Plasma

In fact, the cyclotron resonance does not appear explicitly in the cold model. Because the cyclotron resonance is, in its principle, an interaction between the wave and particle motion. In other words, it involves the microscopic structure of the plasma. We shall use the kinetic theory, to accurately reflect the phenomena occurring at the particle scale. The hot plasma model under certain approximations, leads to a new expression of dielectric tensor can be expressed by a correction of the type:

$$\bar{\bar{\boldsymbol{K}}}_{\boldsymbol{hot}} = \bar{\bar{\boldsymbol{K}}}_{\boldsymbol{cold}}(\omega, B_0, n_{e,0}) + \widetilde{\boldsymbol{K}}(\omega, B_0, n_{e,0}, T_{e,0}) \tag{9}$$

The hot correction $\widetilde{\boldsymbol{K}}$ depends explicitly on the wave vector $\vec{\boldsymbol{k}}$ and the electron temperature at equilibrium, $T_{e,0}$. To calculate the elements of $\overline{\overline{\boldsymbol{K}}}_{\boldsymbol{hot}}$, we start from the relativistic Vlasov equation [2], [10]. In the relativistic formalism, the distribution function of electrons is written as $f_e(\vec{\boldsymbol{r}},\vec{\boldsymbol{p}},t)$ with the relation $\vec{\boldsymbol{p}} = m_{e,0}.\gamma.\vec{\boldsymbol{v}}$ where $m_{e,0}$ is rest mass. The distribution function is solution of the relativistic Vlasov equation given by:

$$\frac{\partial f_e}{\partial t}+\frac{\vec{p}}{m_e\gamma}\frac{\partial f_e}{\partial \vec{r}}-e\left(\vec{E}+\frac{1}{m_e\gamma}\vec{\boldsymbol{p}}\wedge\vec{\boldsymbol{B}}\right)\frac{\partial f_e}{\partial \vec{p}}=0 \qquad (10)$$

Where $m_e^2=m_{e,0}^2+(p/c)^2=m_{e,0}^2\gamma^2$ is the relativistic mass of the electron.

3.2. Relativistic Dielectric Tensor

The distribution function f_e is written as $f_e(\vec{\boldsymbol{r}},\vec{\boldsymbol{p}},t)=f_{e,0}(\vec{\boldsymbol{p}})+f_{e,1}(\vec{\boldsymbol{r}},\vec{\boldsymbol{p}},t)$ the sum of two distribution functions f_{e0} for equilibrium state and f_{e1} for the perturbed state. Similarly to distribution function f_e , the magnetic and electric fields [6], can be written as $\vec{\boldsymbol{B}}=\overrightarrow{\boldsymbol{B_0}}+\overrightarrow{\boldsymbol{B_1}}$ and $\vec{\boldsymbol{E}}=0+\overrightarrow{\boldsymbol{E_1}}$. A perturbed state of linearized Vlasov equation takes the form

$$\frac{df_{e,1}}{dt}=\frac{\partial f_{e,1}}{\partial t}+\frac{\vec{p}}{m_e}\frac{\partial f_{e,1}}{\partial \vec{r}}+\frac{e}{m_e}\left(\vec{\boldsymbol{p}}\wedge\overrightarrow{\boldsymbol{B_0}}\right)\frac{\partial f_{e,1}}{\partial \vec{p}}=-e\left(\vec{\boldsymbol{E}}+\frac{\vec{\boldsymbol{p}}\wedge\vec{\boldsymbol{B}}_{\boldsymbol{1}}}{m_e}\right).\frac{\partial f_{e,0}}{\partial \vec{p}} \qquad (11)$$

The integration of equation (11) gives the relativistic dielectric tensor:

$$\boldsymbol{K_{ij}}=\boldsymbol{\delta_{ij}}-\frac{\omega_p^2}{\omega^2}\frac{\mu^2}{2k_2(\mu)}\int_{-\infty}^{+\infty}d\overline{p}_{II}\int_0^{+\infty}\overline{p}_{\perp}d\overline{p}_{\perp}\frac{e^{-\mu\gamma}}{\gamma}\sum_{n=-\infty}^{n=\infty}\frac{\boldsymbol{P_{i,j}^n}(p_{\perp},p_{II})}{\gamma-n\frac{\omega ce}{\omega}-n_{II}\overline{p}_{II}} \qquad (12)$$

Where $\bar{p}=p/(m_{e,0}c)=\overline{p}_{\perp}+\overline{p}_{II}$, $n_{II}=ck_{II}/\omega$ is the index refraction for parallel direction to $\overrightarrow{\boldsymbol{B_0}}$ and $k_n(z)$ is the modified Bessel function of second kind (or McDonald function) of index n (here $n=2$) and argument z.

If we decompose the dielectric tensor in hermitian and anti-hermitian parts respectively as $\overline{\overline{\boldsymbol{K}}}=\overline{\overline{\boldsymbol{K}}}_{\boldsymbol{h}}+i\overline{\overline{\boldsymbol{K}}}_{\boldsymbol{a}}$. And if one decompose the hot correction $\widetilde{\boldsymbol{K}}$ in real and imaginary part as $\widetilde{\boldsymbol{K}}=\widetilde{\boldsymbol{K}}'+i\widetilde{\boldsymbol{K}}''$. The expression (9) can be written:

$$\overline{\overline{\boldsymbol{K}}}_{\boldsymbol{hot}}=\underbrace{\begin{pmatrix} S+\widetilde{K}_q' & -i(D-\widetilde{K}_q') \\ i(D-\widetilde{K}_q') & S+\widetilde{K}_q' \end{pmatrix}}_{hermitian}+i\underbrace{\begin{pmatrix} \widetilde{K}_q'' & i\widetilde{K}_q'' \\ -i\widetilde{K}_q'' & \widetilde{K}_q'' \end{pmatrix}}_{anti-hermitian} \qquad (13)$$

It can be shown that the first hermitian part $\overline{\overline{\boldsymbol{K}}}_{\boldsymbol{h}}$ characterizes the propagation while the second anti-hermitian part $\overline{\overline{\boldsymbol{K}}}_{\boldsymbol{a}}$ characterizes the absorption [11]. If $T_e\to 0$, we obtain $\overline{\overline{\boldsymbol{K}}}_{\boldsymbol{a}}=0$ and $\overline{\overline{\boldsymbol{K}}}_{\boldsymbol{h}}=\overline{\overline{\boldsymbol{K}}}_{\boldsymbol{cold}}$; which justifies the use of the cold approximation to describe wave propagation [11].

3.3. Absorption Coefficient

We take the viewpoint of geometrical optics by considering a plane monochromatic wave of type $\vec{\boldsymbol{E}}(\vec{\mathbf{r}},t)=\vec{\boldsymbol{E}}(\vec{\boldsymbol{k}},\omega)\,exp\{i[\vec{\boldsymbol{k}}.\vec{\boldsymbol{r}}-\omega t]\}$ for which one trying to describe the dissipation by introducing the concept of absorption coefficient. For there to be absorption, it is necessary that the wave vector $\vec{\boldsymbol{k}}$ is complex like $\vec{\boldsymbol{k}}=\vec{\boldsymbol{k}'}+i\overrightarrow{\boldsymbol{k_a}}''$ and its imaginary part is nonzero, $\overrightarrow{\boldsymbol{k_a}}''=(\omega/c)\vec{\boldsymbol{N}}''\neq 0$. Then the absorption coefficient [8] is given by

$$\alpha = -2k''_a.\frac{\vec{v}_g}{v_g} \quad (14)$$

With $\vec{v_g} = \frac{d\vec{r}}{dt}$ is the group velocity. For the explicit calculation of the absorption coefficient, we introduce another approach based on energy conservation, using the anti-hermitian part of the dielectric tensor. Poynting's theorem [12] writes:

$$\frac{\partial W_{0,t}}{\partial t} + \vec{\nabla}.\vec{S}_{0,t} = \frac{\partial}{\partial t}\frac{1}{2}\left(\frac{|\vec{B}_t|^2}{_0} + \varepsilon_0|\vec{E}_t|^2\right) + \frac{1}{\mu_0}\vec{\nabla}.Re(\vec{E}_t \wedge \vec{B}_t) = -\vec{j}_t.\vec{E}_t \quad (15)$$

Where $\partial W_{0,t}/\partial t$, the instantaneous energy density contains the magnetic $|\vec{B}_t|^2/(2\mu_0)$ and electrostatic $\frac{1}{2}\varepsilon_0|\vec{E}_t|^2$ energies respectively. $\vec{S}_{0,t}$ is the instantaneous Poynting vector in vacuum describing the flow of electromagnetic energy. The source term, $-\vec{j}_t.\vec{E}_t$, describes the interactions of the wave with the plasma. By performing the time average over a few periods of oscillations $\langle\vec{E}_t\rangle t = E_1(\vec{r})\, exp(i\vec{k}.\vec{r})$, and separating explicitly the hermitian and anti-hermitian parts of dielectric tensor introduced into the source term, we can be extracted from equation (15) the absorption coefficient as:

$$\alpha = \frac{\varepsilon_0\omega\vec{E}_1^*\bar{K}_a\vec{E}_1}{|\vec{S}|} \quad (16)$$

Where $\vec{E}_1^*$ is the complex conjugate of $\vec{E_1}$ and $\vec{S} = \vec{S}_0 + \vec{Q}_s$ with $\vec{S}_0 = \frac{1}{4\mu_0}Re(\vec{E}_1^* \wedge \vec{B}_1 + \vec{E}_1 \wedge \vec{B}_1^*)$ and $\vec{Q}_s = -\frac{1}{4}\varepsilon_0\omega\vec{E}_1^*\frac{\partial\overline{\overline{K_h}}}{\partial k}.\vec{E}_1$.

Optical depth or optical thickness is a measure of transparency and is defined as the integral of the absorption coefficient α along the trajectory s of the wave like $\tau = \int -\alpha$, [2], [3], [9]. The total absorbed power P_{abs} in the plasma can then be written as

$$P_{abs} = P_{inj}\,(1 - exp(- \ )) \quad (17)$$

We can see an illustration of the function P_{abs}/P_{inj} in Figure 6 where we define that the plasma is optically thick when τ > 3, that is to say the fraction of absorbed power $P_{abs}/P_{inj} > 95\%$.

The relation of resonance is given by the relativistic cyclotron resonance condition of energy exchange between the wave electron cyclotron and plasma as follows:

$$\gamma - k_{II}v_{II} - n\frac{\omega_{ce}}{\omega} = 0 \quad (18)$$

The term $k_{II}v_{II}$ describes longitudinal Doppler shift [5]. The term $n\omega_{ce}/\omega$ describes the gyration of the electron; n is the order of the harmonic excited. This relation expresses the equality between the frequency of the wave and the relativistic cyclotron frequency of rotation corrected by the Doppler shift which caused by the electron parallel velocity. The energy of resonant electrons at ω_{ce} and given n_{II} can be written as:

$$E = m_e c^2(k_{II}v_{II} + n\frac{\omega_{ce}}{\omega} - 1) \quad (19)$$

3.4. Curve of resonance:

In the relativistic case, the curves of resonance between electron cyclotron waves and plasma are semi-ellipses as shown in Fig.7. (a) in the momentum space $(\bar{p}_{II}, \bar{p}_\perp)$ with the equation derived from (18) is written [13] as

$$\frac{(\bar{p}_{II}-\bar{p}_{II,0})^2}{\alpha_{II}^2} + \frac{\bar{p}_\perp^2}{\alpha_\perp^2} = 1 \quad (20)$$

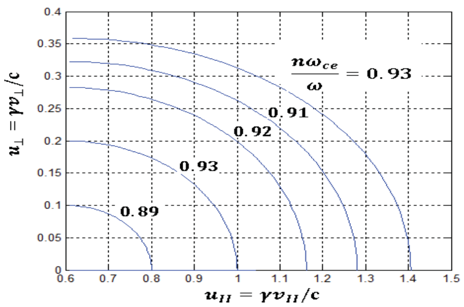
With $\bar{p}_{II,0} = \frac{N_{II}(n\omega_{ce}/\omega)}{1-N_{II}^2}$ for the center of ellipse and the lengths of its semi-axis are given by

$$\alpha_{II} = \frac{\sqrt{(n\omega_{ce}/\omega)^2-(1-N_{II}^2)}}{1-N_{II}^2}, \alpha_\perp = \frac{\sqrt{(n\omega_{ce}/\omega)^2-(1-N_{II}^2)}}{\sqrt{1-N_{II}^2}} \quad (21)$$

- If $(n\omega_{ce}/\omega)^2 < (1 - N_{II}^2)$ any exchange of energy between the wave and the plasma is prohibited.
- If $(1 - N_{II}^2) < (n\omega_{ce}/\omega)^2 < 1$, the wave may transfer its energy to plasma. The absorption is then traditionally described as "up-Shifted".
- If $(n\omega_{ce}/\omega)^2 > 1$, we can expect that the absorption takes place mainly in the vicinity of $\bar{p}_{II} = \bar{p}_{II,0} - \alpha_{II}$. Under these conditions, the absorption is described as "down-shifted".

The Fig.7 (b) is the same as Fig.7.(b) but for perpendicular propagation, so the equation (18) becomes:

$$\gamma - n\frac{\omega_{ce}}{\omega} = 0 \quad (22)$$



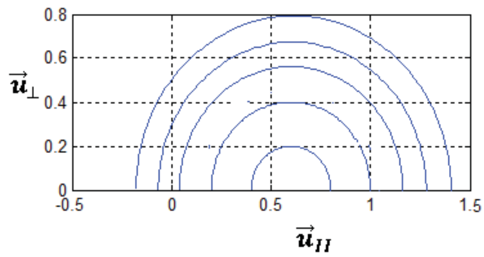


Fig.7. Resonance curves (N_{II} = 0.5) (a) for oblique propagation; (b) for perpendicular propagation

5. Summary

The transfer of energy to the plasma is made by the wave interaction with cyclotron moving electrons in resonance. This transfer of energy by absorption appears as kinetic energy of the electrons which increases the thermal motion in the plasma and hence plasma heating. The application of EC waves to plasmas rests on a wide base of theoretical work which progressed from simple cold plasma models to hot plasma models with fully relativistic physics to quasilinear kinetic Vlasov models. This technique is used in tokamak machines as ITER for additional heating (ECRH) and the generation of non-inductive current drive (ECCD). The power absorbed depends on the optical depth which in turn depends on coefficient of absorption and the order of the excited harmonic for chosen mode generally in perpendicular propagation to magnetic field. The relation of resonance can determine if the curve of resonance is ellipse or a circle according to the propagation oblique or perpendicular.

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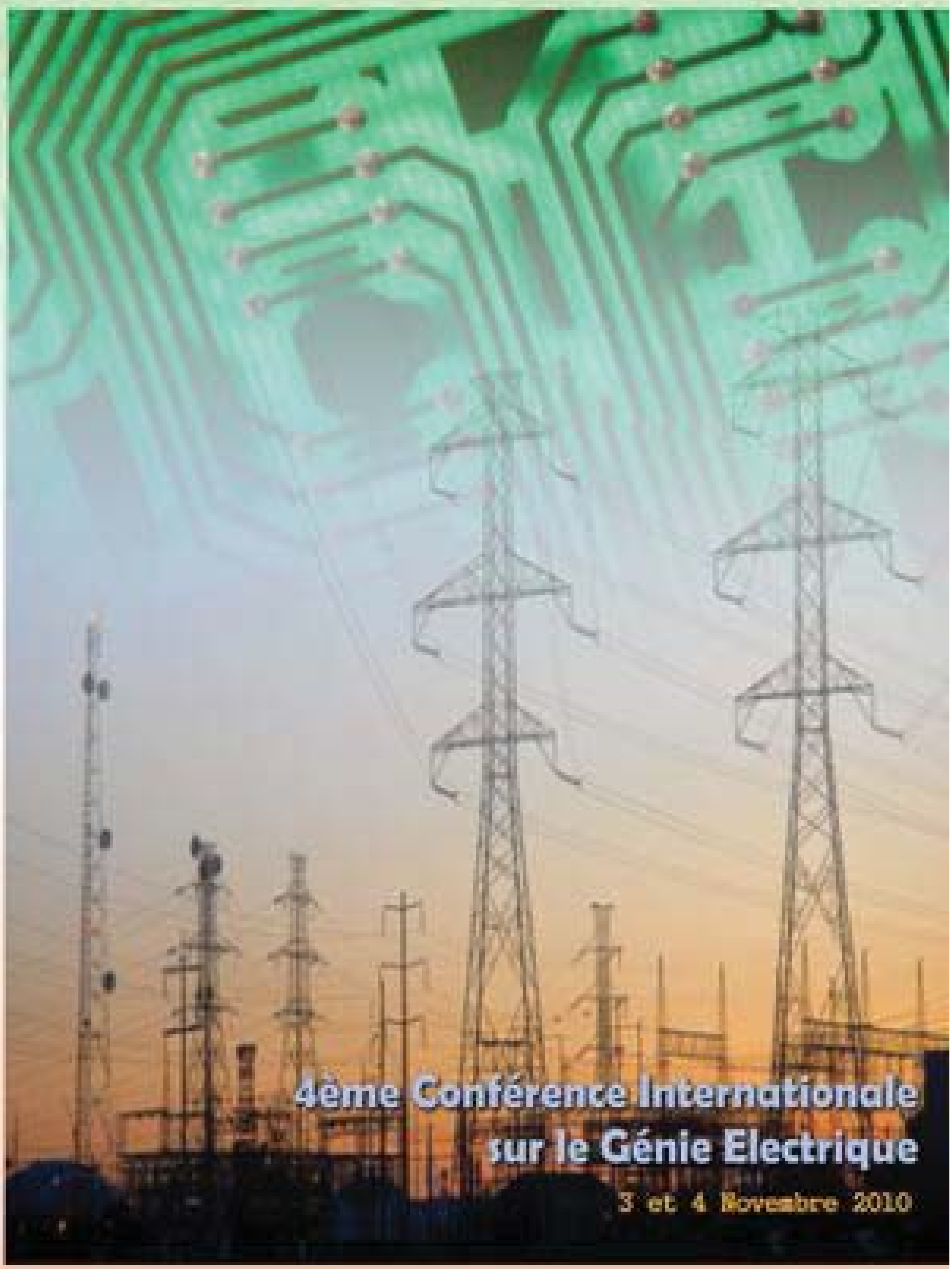

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Study of Alfven Waves in Collisionnels and Collisionless Plasmas

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1. Introduction

A very big variety of waves electromagnetic dispersive can propagate in the plasma. The indication of plasma for such wave can varied in big proportions during its propagation, this is called mode of oscillation. This is resorting to the Colombian interaction between the charged particles that provokes strength of recall as soon as plasma moving out the electric neutrality.

Alfvén waves are waves of magnetohydrodynamic origin resulting from coupling between the magnetic field and velocity field. They have the characteristic be transverse magnetic field and propagate with a speed proportional to the external magnetic field. Its domain of validity is that of large scale with low frequencies like physics of stellar winds and solar physics domains [1].

1.1 Collisionals plasmas

A collisional plasma [2] is a plasma where collisions between particles are extremely frequent as in the case of cold plasma with a fluid approach [3]. In such middle the statistical distribution in energy of the particles is governed by the Boltzmann law ($f(E) =$ exponential $(-E/kT)$, where k is the Boltzmann constant and T the local temperature). This law allows knowledge at each point of space, density, velocity and temperature of the fluid. These types of plasmas can be described by the MHD equations in their fluid approximation. For this, the mean free path of a particle forming the plasma must be smaller than the characteristic scale of spatial gradient of the medium.

1.2 Collisionless plasmas

In the case of collisionless plasmas [2] (eg the solar wind), To describe them, then we must resort to a microscopic description, as kinetic theory [3] that describes the state of the plasma with a distribution function of the positions and velocities $f(x,u,t)$ of each species of particles composing the plasma.

Alfven wave is a simple system of equations of the MHD [3] [5]. These waves occur in many astrophysical and geophysical. For example, the observation of ultra-violet and wind from the sun suggests that the temperature of the solar atmosphere is a few million Kelvin; where energy is transported from the deep layers to surface via Alfven waves.

2. The Maxwell's Equation:

In plasma, it is described by Maxwell's equation of that we write under the shape:

$$\vec{\nabla}.\vec{D} = \rho_{ext} \quad (1)$$

$$\vec{\nabla}.\vec{B} = 0 \quad (2)$$

$$\vec{\nabla}\Lambda\vec{E} = -\frac{\partial\vec{B}}{\partial t} \quad (3)$$

$$\vec{\nabla}\Lambda\vec{H} = \vec{j}_{ext} + \frac{\partial\vec{D}}{\partial t} \quad (4)$$

3. Equations of Propagation and Relation Of Scattering in cold plasma:

The equation of propagation of an electromagnetic wave (varying as $expi(\vec{k}\vec{r} - t.\omega)$) in a collisional plasma [6]ensues of Maxwell's equation and it is express by the relation:

$$\vec{k}\Lambda\vec{k}\Lambda\vec{E} + \frac{\omega^2}{c^2}\overline{\overline{K}}.\vec{E} = \vec{0} \quad (5)$$

Where $\overline{\overline{K}}$ is a cold dielectric tensor of plasma such as :

$$\overline{\overline{K}} = \overline{\overline{I}} + \frac{i\overline{\overline{\sigma}}}{\varepsilon_0 \omega} \qquad (6)$$

$\overline{\overline{\sigma}}$ is the tensor of conductivity of plasma, $\overline{\overline{I}}$ is the tensor identity. It can write also as:

$$\overline{\overline{K}} = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix} \qquad (7)$$

Where S, D and P are the ratings given by Stix

$$S = 1 - \sum_s \frac{\omega_{ps}^2}{(\omega^2 - \sigma_s \omega_{cs}^2)} \qquad (8)$$

$$D = -i \sum_s \frac{\omega_{cs}}{\omega} \frac{\omega_{ps}^2}{(\omega^2 - \sigma_s \omega_{cs}^2)} \qquad (9)$$

$$P = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2} \qquad (10)$$

With $\omega_{ps}^2 = \frac{4\pi n_s q_s^2}{m_s}$ a plasma frequency and $\omega_{cs} = \frac{q_s B_0}{m_s c}$ cyclotron frequency of species s ($s = electron, ion$) and $\sigma_s = qs/|qs|$ is the sign of the charge of species s.

By introducing the refractive index $\vec{n} = \vec{k}c/\omega$.

The equation (5) is written as

$$\begin{pmatrix} S - n^2\cos^2\theta & -iD & n^2\cos^2\theta \\ iD & S - n^2 & 0 \\ n^2\cos^2\theta\sin^2\theta & 0 & P - n^2\sin^2\theta \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0 \qquad (11)$$

The solvability condition of this system implies that its determinant is zero, which gives the following dispersion relation [6]:

$$An^4 + Bn^2 + C = 0 \qquad (12)$$

With

$$A = S\sin^2\theta + P\cos^2\theta \qquad (13)$$

$$B = RL\sin^2\theta + PS(1 + \cos^2\theta) \qquad (14)$$

$$C = PRL \qquad (15)$$

The solution of this quartic equation given in terms of angle θ by the following dispersion relation:

$$\tan^2\theta = -\frac{p(n^2 - R)(n^2 - L)}{(sn^2 - RL)(n^2 - P)} \qquad (16)$$

For the special case of wave propagation *parallel* to the magnetic field and $\theta = 0$, the above expression reduces to

$$P = 0, \; n^2 = R = L \qquad (17)$$

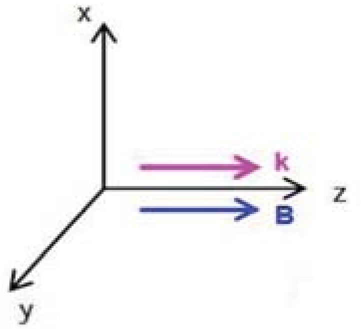


Figure 1: Parallel propagation to the magnetic field $\theta = 0$

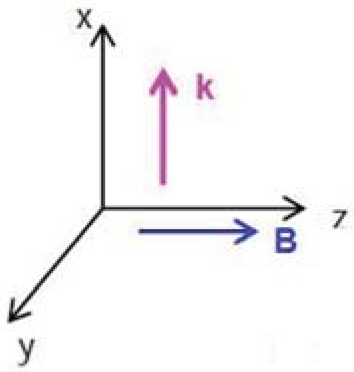
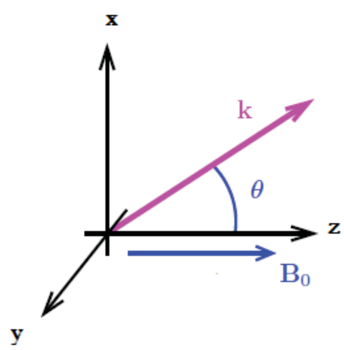


Figure 2: Parallel propagation to the magnetic field $\theta = \pi/2$.

Likewise, for the special case of propagation *perpendicular* to the field and $\theta = \pi/2$, Eq. (16) yields

$$n^2 = \frac{RL}{s} = P \qquad (18)$$

There is another case of study can be conducted for any θ angle: is the *MHD limit* [5],



[3].

Figure 3: Parallel propagation to the magnetic field for any θ .

4. Alfvén waves

Branches of dispersion oblique propagation have a complicated expression because the continuation between θ = π / 2 and θ = 0. In this case the wave propagates with a low frequency approximation checking the magnetohydrodynamic (MHD) $\omega \ll \omega_{ci}, \omega_{pi}$. The elements of dielectric tensor are given by:

$$S = 1 + \frac{\omega_{pi}^2}{\omega_{ci}^2 - \omega^2} + \frac{\omega_{pe}^2}{\omega_{pe}^2 - \omega^2} \approx 1 + \frac{\omega_{pi}^2}{\omega_{ci}^2} = 1 + \frac{c^2}{v_a^2}$$

(19)

$$D \approx \frac{i\omega}{\omega_{ci}} \frac{c^2}{v_a^2} \approx 0 \qquad (20)$$

$$P \approx 1 - \frac{\omega_{pi}^2 + \omega_{pe}^2}{\omega^2} \approx 1 - \frac{c^2}{v_a^2} \frac{\omega_{ci}\omega_{ce}}{\omega^2} \approx -\frac{\omega_{pe}^2}{\omega^2} \gg 1$$

$$P \to \infty \qquad (21)$$

Here, we used the quasi-neutral plasma, which is written $\omega_{pe}^2/\omega_{ce} = -\omega_{pi}^2/\omega_{ci}$

And the system of eigenvalues (11) reduces to

$$\begin{cases} \left(-n^2\cos^2\theta + 1 + \frac{c^2}{v_a^2}\right) E_x = 0 \\ \left(-n^2 + 1 + \frac{c^2}{v_a^2}\right) E_y = 0 \\ (\infty) E_z = 0 \end{cases} \qquad (21)$$

4.1. Shear Alfvén wave (Torsional Alfven wave):

The first equation (21) gives the dispersion relation

$$n^2\cos^2\theta = 1 + \frac{c^2}{v_a^2} \qquad (22)$$

With $Ex \neq 0$ and $Ey = 0$. It is fairly easy to show, from the definitions of the plasma and cyclotron frequencies that $\frac{\omega_{pi}^2}{\omega_{ci}^2} = \frac{c^2}{v_a^2}$. Here, $\rho \simeq nm_i$ is the plasma mass density, and

$$v_a = \sqrt{\frac{B_0^2}{\mu_0 \rho}} \qquad (23)$$

is called the *Alfvén velocity*. Thus, the dispersion relations of the two low-frequency waves can be written

$$\omega \approx k v_a \cos\theta \equiv k_{II} v_a \qquad (24)$$

With a phase velocity

$$v_\varphi \approx v_a^2 \cos^2\theta \qquad (25)$$

It is interesting to note that the magnetic perturbation induces torsion of field lines and is therefore called *slow* or *shear* Alfvén wave [7], [8] (see Figure 2.10 (a)

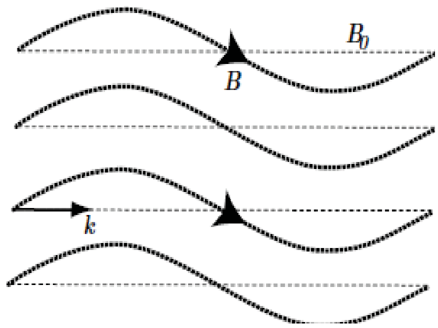


Figure 4: (a) Magnetic field perturbation associated with a shear-Alfvén wave

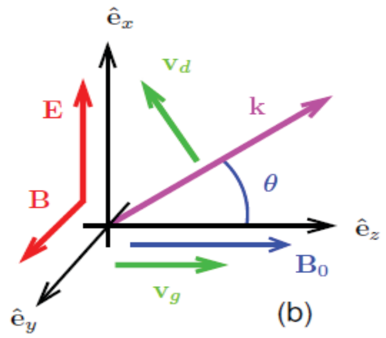


Figure 4: (b) Polarization

4.2. Compressional Alfvén wave

The second solution of (21) gives the dispersion relation

$$n^2 = 1 + \frac{c^2}{v_a^2} \qquad (26)$$

With $Ex = Ez = 0$ and $Ey \neq 0$.

Thus, the dispersion relations of the two low-frequency waves can be written

$$\omega = \frac{k v_a}{\sqrt{1 + v_a^2/c^2}} \approx v_a \qquad (27)$$

With a phase velocity

$$v_\varphi \approx \frac{c}{\sqrt{1 + c^2/v_a^2}} = v_a \qquad (28)$$

Figure 5(a) shows the characteristic distortion of the magnetic field associated with a compressional-Alfvén wave propagating perpendicular to the equilibrium field. Clearly, this wave compresses magnetic field-lines without bending them and this mode is usually called the *fast* or *compressional* Alfven wave also ion magnetosonic wave [7], [8].

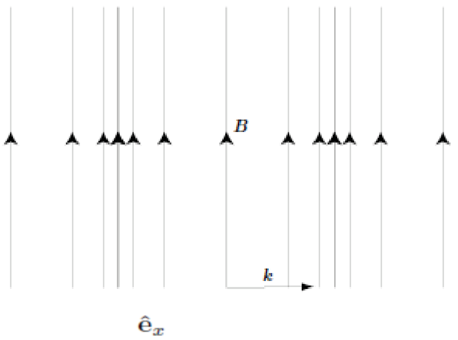


Figure 5: (a) *Magnetic field perturbation associated with a compressional Alfén-wave.*

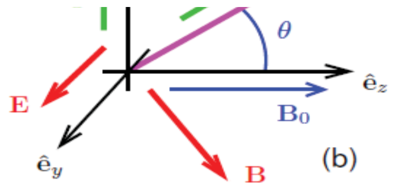
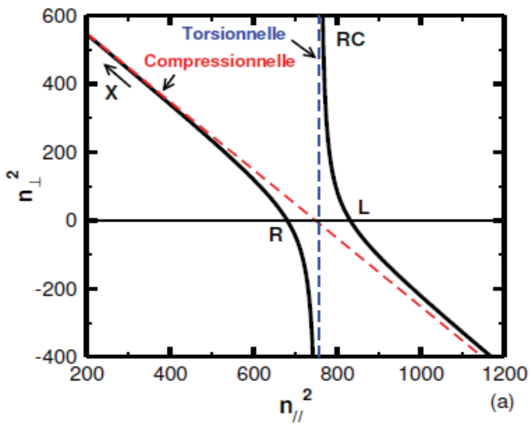


Figure 5: (b) Polarization



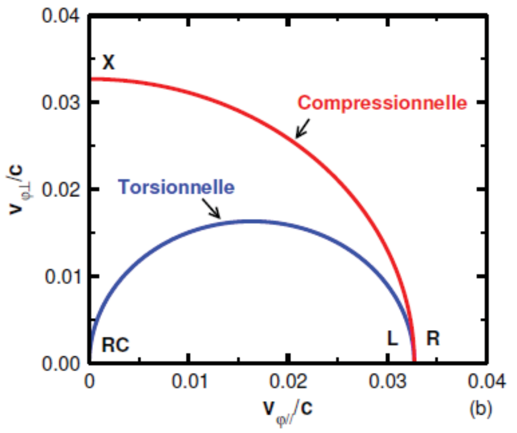


Figure 6: (a) Hyperbola dispersion (b) Surface velocities of phases in a hydrogen plasma with $\omega/\omega_{ci} = 0.1$ et $\omega_{pe}^2/\omega_{ce}{}^2 = 0.4$.

Where"R" and "L" refer to right and left whistlers, respectively. "RC" means the resonance cone and "X" the extraordinary mode. To summarize the characteristics of their dispersion relations shows the hyperbola dispersion and the surface phase velocities of the two waves on Figures 6 (a) and (b). We can see that *shear wave* is related to the branch of the whistler L for propagation parallel, and the resonance cone for propagation perpendicular. The compressional wave belongs to the branch R-X.
Note that the resonance cone has a vertical asymptote, which is associated with the fact that the dispersion relation of the torsional wave does appear by $n_\perp$, then it sets n_{II}.

5. Study of the MHD Waves:

In MHD ($\omega \ll \omega_i$), we find Alfvén waves, that we have already presented above in cold plasma. It is also interesting to study the influence effects of finite temperature. The treatment is however quite tedious .
and here we will use the fluid approximation for the MHD equation dipersion.
The Magnetohydrodynamics (MHD) is the study of the flow of a fluid conductor in a magnetic field [5]. It is the application of the preceding equations to the case of a hot gas, good conductor. The current density $\vec{j}$ is related to the electric field and resistivity by Ohm's Law.

$$\vec{E} = \eta\ \vec{j} \tag{32}$$

In a conductor with a velocity $\vec{v}$ in the presence of a magnetic field, we can write:

$$\vec{E} + \vec{v}\Lambda\vec{B} = \eta\ \vec{j} \tag{33}$$

The preceding equations must be supplemented by an equation of state such as:

$$\frac{d}{dt}\left(p\rho^{-\gamma}\right) = 0 \tag{34}$$

With ρ the charge density, $\gamma = 5/3$ for adiabatic transformation. Differential form is written

$$\left(\frac{\partial}{\partial t} + \vec{v}.\vec{\nabla}\right)\frac{p}{\rho^\gamma} = 0 \qquad (35)$$

In problems of MHD, the electromagnetic field is always with low frequency so that one can neglect the term $d\vec{E}/dt$ in Maxwell equation. The MHD equations are then:

$$\frac{\partial\rho}{\partial t} + \rho\vec{\nabla}.\vec{u} = 0 \qquad (36)$$

$$\rho\frac{\partial\vec{u}}{\partial t} - \frac{1}{\mu_0}.\left(\vec{\nabla}\times\vec{B}\right)\times\overrightarrow{B_0} + \vec{\nabla}P = 0 \qquad (37)$$

$$-\frac{\partial\vec{B}}{\partial t} + \vec{\nabla}\times\left(\vec{u}\times\vec{B}\right) = 0 \qquad (38)$$

$$\frac{\partial}{\partial t}\left(\frac{p}{\rho^\gamma}\right) = 0 \qquad (39)$$

We linearized equations (36) and (39) for obtain the first order (equilibrium flow velocity and equilibrium plasma current are both zero)

$$\frac{\partial\rho}{\partial t} + \rho_0\vec{\nabla}.\vec{v} = 0 \qquad (40)$$

$$\rho_0\frac{\partial\vec{v}}{\partial t} - \frac{1}{\mu_0}.\left(\vec{\nabla}\times\vec{B}\right)\times\overrightarrow{B_0} + \vec{\nabla}p = 0 \qquad (41)$$

$$-\frac{\partial\vec{B}}{\partial t} + \nabla^{\to}\times\left(\vec{v}\times\overrightarrow{B_0}\right) = 0 \qquad (42)$$

$$\frac{\partial\rho}{\partial t}\left(\frac{p}{p_0} - \frac{\gamma\rho}{\rho_0}\right) = 0 \qquad (43)$$

$$\vec{E} + \vec{u}\Lambda\vec{B} = \begin{cases} 0 & MHD \quad ideal \\ \eta\vec{j} & MHD \quad resistive \end{cases} \qquad (44)$$

Here, the subscript 0 denotes an equilibrium quantity ρ_0, p_0, and $\overrightarrow{B_0}$ are constants in a spatially uniform plasma. Perturbed quantities are written without subscripts. For planes waves, perturbed quantities vary like $exp[\,i\,(\vec{k}\cdot\vec{r} - \omega t)]$. It follows that

$$-\omega\rho + \rho_0\vec{k}.\vec{v} = 0 \qquad (45)$$

$$-\omega\rho_0\vec{v} - \frac{1}{\mu_0}.\left(\vec{k}\times\vec{B}\right)\times\overrightarrow{B_0} + \vec{k}\,p = 0 \qquad (46)$$

$$\omega\vec{B} + \vec{k}\times\left(\vec{v}\times\overrightarrow{B_0}\right) = 0 \qquad (47)$$

$$-\omega\left(\frac{p}{p_0} - \frac{\gamma\rho}{\rho_0}\right) = 0 \qquad (48)$$

Assuming that $\omega \neq 0$, the above equations yield

$$\rho = \rho_0\frac{\vec{k}\vec{v}}{\omega} \qquad (49)$$

$$p = \gamma p_0\frac{\vec{k}\vec{v}}{\omega} \qquad (50)$$

$$\vec{B} = \frac{(\vec{k}\vec{v})\overrightarrow{B_0} - (\vec{k}\overrightarrow{B_0})}{\omega} \qquad (51)$$

Substitution of these expressions into the linearized equation of motion, Eq. (46), gives

$$\left[\omega^2 - \frac{(\vec{k}\overrightarrow{B_0})^2}{\mu_0\rho_0}\right]\vec{v} = \left\{\left[\frac{\gamma B_0}{\rho_0} + \frac{B_0^2}{\mu_0\rho_0}\right]\vec{k} - \frac{(\vec{k}\overrightarrow{B_0})}{\mu_0\rho_0}\right\}(\vec{k}\vec{v}) - \frac{(\vec{k}\overrightarrow{B_0})(\vec{v}\overrightarrow{B_0})}{\mu_0\rho_0}\vec{k} \qquad (52)$$

We can assume, without loss of generality, that the equilibrium magnetic field $\overrightarrow{B_0}$ is directed along the z-axis, and that the wave-vector $\vec{k}$ lies in the (zx) plane. Let θ be the angle subtended between $\overrightarrow{B_0}$ and $\vec{k}$. Equation (52) reduces to the eigenvalue equation

$$\begin{pmatrix} \omega^2 - k^2v_a^2 - k^2v_s^2sin^2\theta & 0 & -k^2v_s^2sin\theta cos\theta \\ 0 & \omega^2 - k^2v_a^2cos^2\theta & 0 \\ -k^2v_s^2sin\theta cos\theta & 0 & \omega^2 - k^2v_a^2cos^2\theta \end{pmatrix} \times \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = 0 \qquad (53)$$

Where we introduced the Alfvén speed, encountered already in precedent section and which is written here

$$v_a = \sqrt{\frac{B_0^2}{\mu_0\rho_0}} \qquad (54)$$

And

$$v_s = \sqrt{\frac{\gamma p_0}{\rho_0}} \qquad (55)$$

is the *sound speed*. The solubility condition for Eq. (53) is that the determinant of the square matrix is zero. This yields the dispersion relation

$$(\omega^2 - k^2\,{v_a}^2\,cos^2\theta)[\omega^4 - \omega^2k^2(v_a^2 + v_s^2) + k^4v_a^2v_s^2cos^2\theta] = 0 \qquad (56)$$

There are *three* independent roots of the above dispersion relation, corresponding to the three different types of wave that can propagate through an MHD plasma. The first, and most obvious, root is

$$\omega = k v_a \cos\theta \qquad (57)$$

which has the associated eigenvector $(0, v_y, 0)$. This root is characterized by both $\vec{k}.\vec{v} = 0$ and $\vec{v}.\vec{B_0} = 0$. It immediately follows from Eqs. (50) and (51) that there is *zero* perturbation of the plasma density or pressure associated with this root. In fact, this root can easily be identified as

	v_{gII}	$v_{g\perp}$
Alfvèn mode	v_a	0
Fast mode	$v_+ sin\theta[1 + F_1 sin^2\theta]$	$v_+ sin\theta[1 + F_1 cos^2\theta]$
Slow mode	$v_- cos\theta[1 + F_2 sin^2\theta]$	$v_- cos\theta[1 + F_2 cos^2\theta]$

the *shear-Alfvén wave*, which was introduced in above.The second member leads to two solutions

$$\omega\pm = \frac{k}{\sqrt{2}}[(v_a^2 + v_s^2) \pm$$

$$\pm\sqrt{(v_a^2 + v_s^2)^2 - 4 v_a^2 v_s^2 \cos^2\theta)}]^{1/2} \qquad (58)$$

The first solution is generally termed the *fast magnetosonic wave*, or fast wave, for short whereas the other solution is usually called the *slow magnetosonic wave*, or slow wave. The eigenvectors for these waves are $(v_x, 0, v_z)$. It follows that $\vec{k}.\vec{v} \neq 0$ and $\vec{v}.\vec{B} \neq 0$. Hence, these waves are associated with non-zero perturbations in the plasma density and pressure.
Assuming that the pressure is zero, cie, $v_s = 0$ for the cold-plasma limit we see that $\omega_+ = k v_a$ and this solution corresponds to the compressional Alfven wave. Thus, we can identify the fast wave as the compressional-Alfvén wave modified by a non-zero plasma pressure.
The second solution gives $\omega_- = 0$.
So it's a slow wave (remember $\omega_- < \omega_+$) strictly associated with pressure effects and in the limit $v_a \gg v_s$, which is appropriate to low-β plasmas [richards], the dispersion relation for the slow wave reduces to

$$\omega \simeq k v_s \cos\theta \qquad (59)$$

This is actually the dispersion relation of a sound wave propagating *along* magnetic field-lines. Thus, in low-β plasmas the slow wave is a sound wave modified by the presence of the magnetic field.
To further analyze the propagation of these modes, it is instructive to represent their group velocities where the group velocity is defined by its two components parallel and perpendicular to $\overrightarrow{B_0}$.

$$v_{gII} = \frac{\partial\omega}{\partial k_x} \qquad (60)$$

$$v_{g\perp} = \frac{\partial\omega}{\partial k_z} \qquad (61)$$

Then we can draw the following table, providing the various expressions of the group velocity for the three modes
Table 1: the group velocity for the three modes.

With

$$F_1 = \frac{v_c^2}{v_+^2}\frac{1}{1-2v_+^2/(v_a^2+v_s^2)} \qquad (62)$$

And

$$F_2 = \frac{v_c^2}{v_-^2}\frac{1}{1-2v_-^2/(v_a^2+v_s^2)} \qquad (63)$$

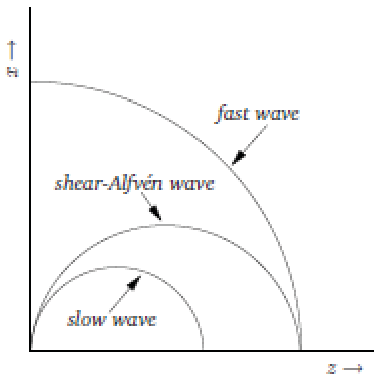


Figure 7: Phase velocities of the three MHD waves in the x-z plane.

Figure 7 shows the phase velocities of the three MHD waves plotted in the x-z plane for a low-β plasma in which $v_s < v_a$. It can be seen that the slow wave always has a smaller phase velocity than the shear-Alfvén wave, which, in turn, always has a smaller phase velocity than the fast wave.

6. Conclusions

In this communication, we present the study of Alfvén waves which are waves of magnetohydrodynamic origin resulting from coupling between the magnetic field and velocity field. They have the characteristic be transverse magnetic field and propagate with a speed proportional to the external magnetic field. It is a simple solution of the the MHD system equations. These waves occur in many astrophysical and geophysical. Its domain of validity is that of large scale with low frequencies like physics of stellar winds and solar physics domains

There are *three* different types of wave that can propagate through an MHD plasma. The first type is termed as the shear-Alfvén wave.

The properties of these wave in a warm collisionless (*i.e.*, non-zero pressure) plasma are unchanged from those we found earlier in a cold collisional plasma. The two others types correspond to fast magnetosonic and wave the slow magnetosonic wave which are associated with non-zero perturbations in the plasma density and pressure, and also involve plasma motion parallel, as well as perpendicular, to the magnetic field. Their dispersion relations are likely to undergo significant modification in collisionless plasmas. Thus, we can identify the fast wave as the compressional-Alfvén wave modified by a non-zero plasma pressure.

In low-β plasmas the slow wave is a sound wave modified by the presence of the magnetic field.

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Abstract

The study of Alfvén waves which are waves of magnetohydrodynamic origin resulting from coupling between the magnetic field and velocity field. They have the characteristic be transverse magnetic field and propagate with a speed proportional to the external magnetic field. It is a simple solution of the MHD system equations. These waves occur in many astrophysical and geophysical. Its domain of validity is that of large scale with low frequencies like physics of stellar winds and solar physics domains

There are *three* different types of wave that can propagate through MHD plasma. The first type is termed as the shear-Alfvén wave.

The properties of these wave in a warm collisionless (*i.e.*, non-zero pressure) plasma are unchanged from those we found earlier in a cold collisional plasma. The two others types correspond to fast magnetosonic and wave the slow magnetosonic wave which are associated with non-zero perturbations in the plasma density and pressure, and also involve plasma motion parallel, as well as perpendicular, to the magnetic field. Their dispersion relations are likely to undergo significant modification in collisionless plasmas. Thus, we can identify the fast wave as the compressional-Alfvén wave modified by a non-zero plasma pressure.

Keys words:

Alfvén waves, MHD, collisionless, collisional, plasma.

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Comparative study between kinetic and fluid models at the core and the edge of the tokamak plasma

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Abstract:

In this work, we present a comparative study between kinetic and fluids models corresponding to the core and the edge of tokamak plasma. A kinetic description is often necessary for collisionless plasmas as in the Maxwellian plasma and the fluid one is appropriate where collisions play an important role as in the plasma edge. Both descriptions have advantages and inconveniences may not be competing but complementary. For this reason, kinetic-fluid hybrid models are implemented very often since they combine the accuracy of kinetic models with short computational times of fluid models.
Key words: kinetic, fluid, model, hybrid, plasma, tokamak.

I. Introduction

The challenge for research on magnetic confinement fusion is effectively confining a plasma inside a reactor (tokamak) with a density and temperature sufficient to maintain thermonuclear fusion reactions and thereby the production of energy. The plasma confinement time is limited by diffusion losses of particles and heat. These losses are mainly produced by a phenomenon of turbulent transport (from the center toward the edge of the plasma) generated by micro-instabilities that develops in plasma and which simulation models are required. Modeling of plasma is to explain the motion of a charged particle under the effect of all internal and external electromagnetic fields. In general, plasma consists of very important number of particles, 10^{10} and more. The microscopic model describing the interactions of two to two particles is not used in a simulation because it would be far too expensive. We must therefore find approximate models which, while remaining sufficiently precise can reach a reasonable computational cost. There is actually a hierarchy of models describing the evolution of plasma. The basic model of the hierarchy is the most accurate is the N –body model, then there are intermediate models called kinetic and are based on a statistical description of the particle distribution in phase space and finally macroscopic models or fluid that identify each species of particles of plasma as fluid. In this paper we make a comparison between the kinetic and fluid models.

II. Reactor of controlled thermonuclear fusion

The fusion reaction the most accessible is to fuse nuclei of Deuterium and Tritium for obtain a Helium atom and a neutron high energy which will be used to produce the heat necessary to produce electricity (see fig. 1).

$$D + T \rightarrow {}^{4}He\ (3.5\ MeV) + n\ (14.1\ MeV)$$

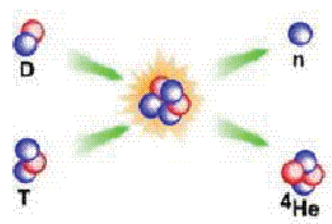
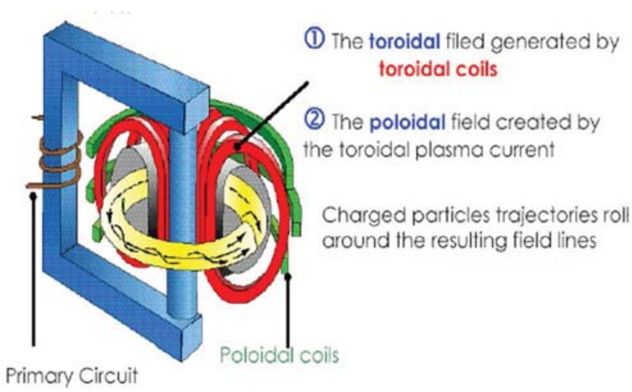


Fig. 1– The fusion reaction of Deuterium-Tritium

In thermonuclear fusion reactor “tokamak” [1], the charged particles that constitute the hot plasma are confined by a magnetic field inside a torus [2], [3] as shown in figure 2. The magnetic forces acting on particles moving in the plasma prevent the plasma to touch the chamber walls. The current that generates the magnetic field is induced in the plasma itself and heated it at the same time. The poloidal magnetic field is created by a toroidal current circulating in the plasma itself, which becomes the secondary of a transformator [1] (see fig. 2).

As shown in figure 3, **ITER**, *The International Thermonuclear Experimental Reactor* is an international project with collaboration of Canada, South Korea, United States, Japan, India, European Union (Switzerland), Russia to design and build a large experimental fusion reactor based on tokamak concept in France, in order to demonstrate the scientific and technical feasibility of producing



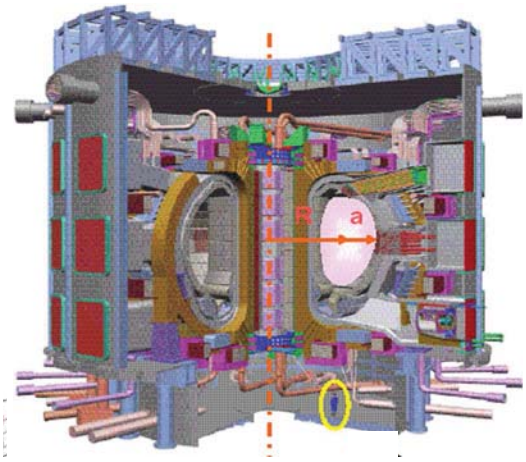


Fig. 2: Tokamak configuration Fig. 3: ITER

electricity through fusion energy with important resources into fuel and low impact on environment. This project began in 2005 and be fully operational by 2050.

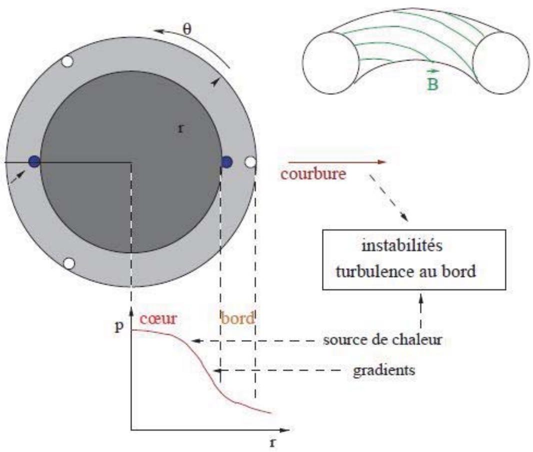


Fig. 4: Different regions of Tokamak

There are three distinct regions in the tokamak plasma (see Fig.4): the core of the plasma, fusion reactions take place, the region called "gradient", characterized by large gradients of density and temperature, and the region known as the “edge”, where the gradients are reduced by strong turbulence [4]

III. Turbulence and transport

This is a very common phenomenon, which can be observed in fluids and encountered in everyday life. If we start to heat water on a stove, you can notice the convective motions that appear soon after. By increasing the power of fire, these movements become progressively more violent and irregular. This is called "*turbulence*". The effect of turbulence in plasmas is the same in water, is the increased transport of matter and energy. Under the conditions of operation of tokamaks, the combined effect of fluctuating electric and magnetic fields is at the origin of *anomalous transport* [5].

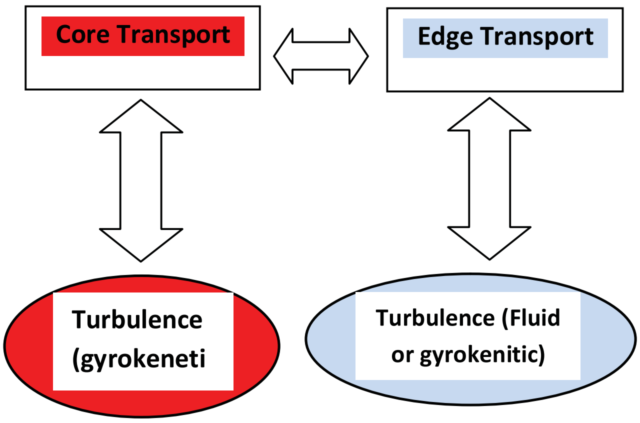


Fig. 5: Transport phenomena and turbulence in the core and edge the plasma [6]

The fluctuating electric field gives rise to an amplification of the movement of particles through the field lines. The magnetic fluctuations cause a distortion of field lines. The loss of energy and matter are related to the particles that move freely along the field lines. This anomalous transport, gives rise to important theoretical developments. If the linear theory is now well established and can predict the conditions under which a wave becomes unstable, it is no longer valid when the wave grows, and you have to move to more complex nonlinear models to simulate the evolution instability.

In practice the study of plasma *turbulence* requires solving Maxwell's equations coupled to calculate the plasma response to the perturbation of the electromagnetic field. This response is obtained using either a description fluid or kinetic. It depends on the transport is at the core or at the edge of the tokamak plasma. We talk about the turbulence which is purely kinetic or gyrokinetic [7] at the core (hot plasma) but it may take one of two descriptions at the plasma edge (cold plasma), as shown in fig. 5. Solving the equations 3D of fluid turbulence is certainly the easiest and quickest as numerical point of view, that solving the kinetic equation of Vlasov-6D. Yet we know that a fluid description overestimates the turbulent flow over a kinetic description.

IV. Kinetic model

The model generally used to study the behavior of plasma particles is based on a kinetic description of plasma using the Vlasov equation [8]. The latter is coupled with Maxwell's equations or Poisson for describing the evolution of electric and magnetic fields. The Vlasov equation characterizes the evolution in time and space distribution of particles in collisionless plasma.

We consider the motion of n particles in phase space $(\vec{x}, \vec{v})$, (position, speed), self-consistent interaction through Coulomb forces and external fields. To simplify the space is considered a single dimension along $\overrightarrow{ox}$, then the density fluctuations are expected along this longitudinal axis $(\vec{E} = E\overrightarrow{e_x}, \vec{v} = v\overrightarrow{e_x}, \vec{B} = B\overrightarrow{e_x})$. If the motion is Hamiltonian: $x' = \frac{\partial_H}{\partial v}$ and $v' = -\frac{\partial_H}{\partial x}$. By setting the density in phase space by the distribution function of particle velocity $f(\vec{x}; \vec{v}; t)$. From the Boltzmann equation [9], we have:

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial x} + \frac{q}{m}\left(\vec{E} + \vec{v} \wedge \vec{B}\right)\frac{\partial f}{\partial v} = \frac{Df}{Dt}\bigg|_{collision} \quad (1)$$

For species s and by neglecting the collisions, we can write a kinetic Vlasov equation of the form

$$\frac{\partial f_s}{\partial t} + v\frac{\partial f_s}{\partial x} + \frac{q_s}{m_s}\left(\vec{E} + \vec{v} \wedge \vec{B}\right)\frac{\partial f_s}{\partial v} = 0 \quad (2)$$

It recognizes the equations of motion of particles in the macroscopic electromagnetic field $(\vec{E}\,,\vec{B})$.
This field itself is described by Maxwell's equations

$$\vec{\nabla}.\vec{\mathrm{E}} = \frac{\rho}{\varepsilon_0} \quad (3)$$

$$\vec{\nabla}.\vec{\mathrm{B}} = 0 \quad (4)$$

$$\vec{\nabla}\wedge\vec{\mathrm{E}} = -\frac{\partial\vec{\mathrm{B}}}{\partial \mathrm{t}} \quad (6)$$

$$\vec{\nabla}\wedge\vec{\mathrm{B}} = {}_0\vec{\mathrm{J}} + \frac{1}{\mathrm{c}^2}\frac{\partial\vec{\mathrm{E}}}{\partial \mathrm{t}} \quad (7)$$

The system consists of the Vlasov equation (2) and Maxwell equations (3)-(7) is closed, called Vlasov-Maxwell system. As part of the kinetic theory, since the fields $\vec{E}$ and $\vec{B}$ are non static quantities and non-discrete locally, they are considered as average values over a limited volume of a sphere whose radius is the *Debye length*.
In the absence of magnetic field applied from outside, the field $\vec{B}$ will be zero (non-relativistic case), the isotropic medium is said electrostatic; the Lorentz force reduces to an electric force $q\vec{E}\,(x,t)$ and the system is Vlasov-Poisson [10] and the equation (2) becomes:

$$\frac{\partial f_s}{\partial t} + \vec{v}\frac{\partial f_s}{\partial \vec{x}} + \frac{q_s\vec{E}}{m_s}\frac{\partial f_s}{\partial \vec{v}} = 0 \quad (8)$$

The source terms of Maxwell's equations, the charge density $\rho(x,t)$ and current density$\vec{J}\,(x;\,t)$ are expressed from the distribution functions of different species of particles$\int f_s(x,v,t)dv$ using relations:

$$\rho(x,t) = \sum_s q_s \int f_s(x,v,t)dv \quad (9)$$

$$\vec{J}(x,t) = \sum_s q_s \int f_s(x,v,t)\vec{v}dv \quad (10)$$

When binary collisions between particles are dominant compared to the effects of average field. The distribution function f satisfies the Boltzmann equation

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} = Q(f,f) \quad (11)$$

Where Q is the collision operator nonlinear Boltzmann.

V. fluid models

The distribution function $f(x,v,t)$ measures in fact the number of electrons (electron species s = electron) in the volume $dx.dv$ f phase space around the coordinates (x,v). Knowledge of $f(x,v,t)$ can therefore be reached by different macroscopic quantities « fluid » which are in fact different moments [8], [11] of the distribution function f :
The local density of particles $n(\vec{x}\,;\,t)$*:*

$$n(\vec{x}\,,t) = \int f(\vec{x},\vec{v},t)d\vec{v} \quad (12)$$

The average velocity $\vec{u}\,(\vec{x}\,;\,t)$

$$\vec{u}(\vec{x}\,,t).n(\vec{x}\,,t) = \int f(\vec{x},\vec{v},t).\vec{v}.d\vec{v} \quad (13)$$

The kinetic pressure tensor $\bar{\bar{P}}\,(\vec{x}\,,t)$ *is defined by*

$$\bar{\bar{P}}(\vec{x}\,,t) = m\int f(\vec{x},\vec{v},t).\big(\vec{v}-\vec{u}(\vec{x},t)\big)\otimes\big(\vec{v}-\vec{u}(\vec{x},t)\big).d\vec{v} \quad (14)$$

The scalar pressure is the third of the trace of the pressure tensor

$$p(x,t) = \frac{Tr(P)}{3} = \frac{m}{3}\int f(x,v,t).(v-u(x,t))^2.dv \quad (15)$$

We defines *the temperature* $\mathrm{T}(\vec{x}\,,t)$ from the pressure by

$$T(\vec{x},t) = \frac{p(\vec{x},t)}{n(\vec{x},t)} \quad (16)$$

The energy flow is a vector defined by

$$Q(x,t) = \frac{m}{2}\int f(\vec{x},\vec{v},t).v^2\vec{v}(\vec{x},t).d\vec{v} \quad (17)$$

Vlasov-Poisson system (or Vlasov-Maxwell in the general case) is the basic system to describe the collective effects in plasma. But given the difficulty of solving the Vlasov-Maxwell system, we are often used fluid model to describe these phenomena. The idea is, from the Vlasov equation, we find the equations for the different macroscopic quantities introduced above (12), (13), (14), etc. .. First note:

1- $\vec{v}\,\overrightarrow{\nabla_x} f = \overrightarrow{\nabla_x}(\vec{v}\,.f)$; because $\vec{v}$ est independent de $\vec{x}$.
2- $\vec{E}\,(\vec{x}\,;\,t)$ does not depend $\vec{v}$:
3- The ith component of $\vec{v}\wedge\vec{B}\,(\vec{x}\,,t)$ is independent of vi such that

$$\vec{v}\wedge\vec{B}\,(\vec{x}\,,t) = \begin{pmatrix} v_2B_3(x,t) - v_3B_2(x,t) \\ v_3B_1(x,t) - v_1B_3(x,t) \\ v_1B_2(x,t) - v_2B_1(x,t) \end{pmatrix} \tag{18}$$

4- $\left(\vec{E}(x,t) + \vec{v}\wedge\vec{B}(x,t)\right)\nabla_v.f = \nabla_v\,[f(\vec{E}\,(x,t) + \vec{v}\wedge\vec{B}\,(x,t))]$

By integrating the Vlasov equation (2) with respect to speed, we get the conservation equation of particle:

$$\frac{\partial n}{\partial t} + \vec{\nabla}(n\vec{u}) = 0 \tag{19}$$

By multiplying the Vlasov equation by mv and integrating over v, we obtain the equation of particle motion[11], [12]:

$$m\frac{\partial}{\partial t}(n\vec{u}) + m\nabla.(n\vec{u}\otimes\vec{u}) + \vec{\nabla}\,P = qn(\vec{E}\,+\vec{u}\wedge\vec{B}\,) \tag{20}$$

p is assumed scalar for an isotropic medium.
Finally, by multiplying the Vlasov equation by $\frac{1}{2}\,mv^2 = \frac{1}{2}\,mv.v$ and integrating over v, we obtain

$$\frac{\partial}{\partial t}\left(\frac{3}{2}p + \frac{1}{2}mnu^2\right) + \vec{\nabla}.\vec{Q} = \vec{E}.(q.n.\vec{u}) \tag{21}$$

We could continue to calculate moments of f by repeating the process and integrating then multiplying but we see a new expression each time showed a higher order. This gives a hierarchy of equations; to stop the hierarchy we introduce a closure relation which is none other than a state relation between the fluids quantities.
In our case, we will use as a closure relation to the physical property that the thermodynamic equilibrium distribution function tends to a Maxwellian distribution function, we note $f_M(x,v,t)$ and that the express under certain assumption on quantities $n(x,t)$; $u(x,t)$; $T(x,t)$ as:

$$fM(x,v,t) = \frac{n(x,t)}{\left(\frac{2\pi T(x,t)}{m}\right)^{\frac{3}{2}}}\,e^{-\frac{(v-u(x,t))^2}{2T(x,t)/m}} \tag{22}$$

We also introduce a classical grandeur in plasma physics is the thermal velocity of the particle species considered

$$v_{th} = \sqrt{\frac{T}{m}} \tag{23}$$

One can easily verify that the first three moments of the distribution function fM are consistent with the definition of macroscopic quantities n; u and T defined for any distribution function. It has in fact easily by each time the change of variable $\omega = \frac{v-u}{v_{th}}$

$$\int f_M(x,v,t)dv = n(x\,,t) \tag{24}$$

$$\int f_M(x,v,t).v.dv = n(x\,,t).u(x\,,t) \tag{25}$$

$$\int f_M(x,v,t).(v-u)^2.dv = 3n(x,t).T(x\,,t)/m \tag{26}$$

Moreover, replacing f by fM in the definitions of pressure tensors $\bar{\bar{P}}$ and energy flow $\vec{Q}$, these terms can be expressed also in terms of n; u and T which allows us to obtain a closed system with these three unknowns, contrary to case of any distribution function f. Values are found:

$$\bar{\bar{P}} = n.T.\bar{\bar{I}} \tag{27}$$

With $\bar{\bar{I}}$ unity matrix of order 3 × 3 and

$$Q = \frac{5}{2}nTu + \frac{m}{2}nu^2u = \frac{5}{2}pu + \frac{m}{2}nu^2u \tag{28}$$

Finally, in referring expressions P and Q in (19), (20) and (21). We obtain the fluid equations for particle species of plasma:

$$\frac{\partial n}{\partial t} + \overrightarrow{\nabla_x}(n\vec{u}) = 0 \tag{29}$$

$$m\frac{\partial}{\partial t}(n\vec{u}) + m\nabla.(n\vec{u}\otimes\vec{u}) + \vec{\nabla} P = qn(\vec{E} + \vec{u}\wedge\vec{B}) \quad (30)$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2}p + \frac{1}{2}mnu^2\right) + \vec{\nabla}.\vec{Q} = \vec{E}.(q.n.\vec{u}) \quad (31)$$

In three dimensions, these equations correspond to a system of five scalar equations with five unknowns scalar which are the density n, the three components of average velocity $\vec{u}$ and scalar pressure p. These equations must of course be coupled with Maxwell equations for calculating the electromagnetic field, for a species of particles $\rho = qn$ and $\vec{j} = qn\vec{u}$: Note also that as a simplification sometimes used an approximation of cold plasma which is at $T = 0$ and therefore $p = 0$. We did not need in this case that the first two equations.

1. MHD model :

The Magnetohydrodynamics (MHD) is the study of the flow of a fluid conductor in a magnetic field [13]. It is the application of the preceding equations to the case of a hot gas, good conductor. The current density $\vec{j}$ is related to the electric field and resistivity by Ohm's Law

$$\vec{E} = \eta\,\vec{j} \quad (32)$$

In a conductor with a velocity u in the presence of a magnetic field, we can write:

$$\vec{E} + \vec{u}\Lambda\vec{B} = \eta\,\vec{j} \quad (33)$$

The preceding equations must be supplemented by an equation of state such as:

$$\frac{d}{dt}\left(p\rho^{-\gamma}\right) = 0 \quad (34)$$

With ρ l the charge density, $\gamma = 5/3$ for adiabatic transformation. Differential form is written

$$\left(\frac{\partial}{\partial t} + \vec{u}.\vec{\nabla}\right)\frac{p}{\rho^{\gamma}} = 0 \quad (35)$$

In problems of MHD, the electromagnetic field is always with low frequency so that one can neglect the term $d\vec{E}/dt$ in Maxwell equation. The MHD equations are then:

$$\frac{\partial n}{\partial t} + \vec{\nabla}(n\vec{u}) = 0 \quad (36)$$

$$m\frac{\partial}{\partial t}(n\vec{u}) + m\nabla.(n\vec{u}\otimes\vec{u}) + \vec{\nabla} P = qn(\vec{E} + \vec{u}\wedge\vec{B}) \quad (37)$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2}p + \frac{1}{2}mnu^2\right) + \vec{\nabla}.\vec{Q} = \vec{E}.(q.n.\vec{u}) \quad (38)$$

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho v) = 0 \quad (39)$$

$$\vec{E} + \vec{u}\Lambda\vec{B} = \begin{cases} 0 & MHD \quad ideal \\ \eta\,\vec{j} & MHD \quad resistive \end{cases} \quad (40)$$

$$\frac{\partial\vec{B}}{\partial t} = -\vec{\nabla}\Lambda\vec{E} \quad (41)$$

$$\vec{\nabla}\Lambda\vec{B} = \mu_0\,\vec{j} \quad (42)$$

$$\left(\frac{\partial}{\partial t} + \vec{u}.\vec{\nabla}\right)p = \gamma\, p\vec{\nabla}.\vec{u} \quad (43)$$

2. Ideal MHD model:

The MHD model seen above is widely used to study the stability of magnetic confinement. It is a basic approximation to treat the global stability of the plasma ignoring its microscopic structure, whose effects appear in a second approximation, e.g. in the form of an anomalous transport of particle or heat that does not call into question the global stability. The simplest instabilities are directly resulting of ideal MHD in which we neglect the resistivity. Resistive instabilities, however, play an important role in toroidal configurations and in particular in the Tokamak. Regarding the equilibrium of ideal MHD is obtained directly from the equations of MHD (20) that the field $\vec{B}$, pressure $\vec{p}$ and current density $\vec{j}$ must satisfy the following relations:

$$\vec{B}.\nabla p = 0, \vec{j}.\nabla p = 0$$

In a confined plasma $\nabla p \neq 0$ everywhere, then we have surfaces of $p = cst$ are called *magnetic surfaces*.

IV. Comparison between fluid and kinetic models

Fluid models describe plasmas in terms of macroscopic quantities such as density and average speed around each position, the mean energy. One of the simple fluid models, magnetohydrodynamics, which treats the plasma as a single fluid governed by a combination of Maxwell's equations and Vlasov equations. A more general picture is that of two-fluid plasma, where ions and electrons are described separately.

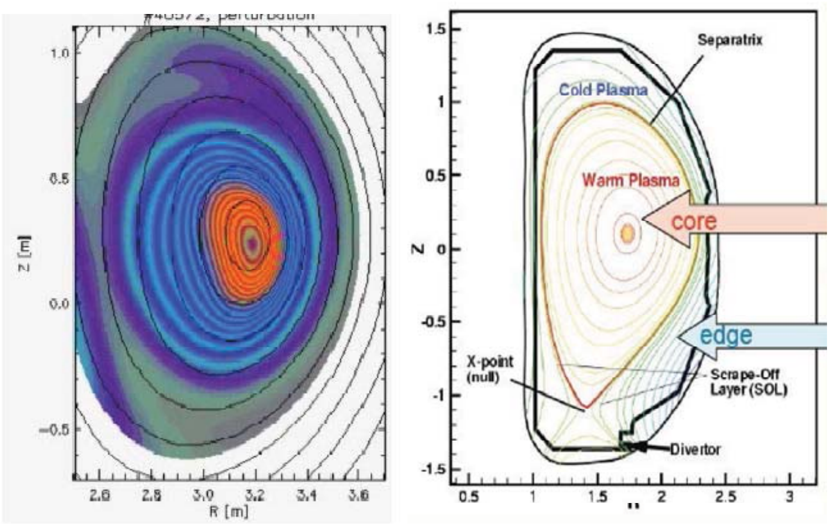


Fig.6: The core (collisionless) and edge (collisional) of the plasma in a tokamak [1], [6]

Fluid models are often accurate when collisionality is sufficiently high to maintain the plasma velocity distribution close to a Maxwell-Boltzmann distribution. Because fluid models usually describe the plasma in terms of a single flow at a certain temperature at every location in space, they cannot neither take the structures of the velocity space like beams or double layers nor solve the effect of wave-particles. This description is appropriate where collisions play an important role as in the plasma edge (See Fig. 6).

Kinetic models describe the distribution function of particle velocity at each point in the plasma, and therefore should not assume a Maxwell-Boltzmann system. A kinetic description is often necessary for collisionless plasmas. There are two common methods of kinetic description of plasma. One is based on representing the smoothed distribution function on a grid of velocity and position. The other, known as particle-in-cell (PIC) technique [14], includes kinetic information by following the trajectories of a large number of individual particles. Kinetic models are generally more computationally intensive than fluid models. The Vlasov equation can be used to describe the dynamics of a system of charged particles interacting with an electromagnetic field. In magnetized plasmas, a kinetic or gyrokinetic approach can significantly reduce the computational expense of a fully kinetic simulation. This description is appropriate when collisions are very low or null in the Maxwellian plasma of the core of tokamak. In this case the electrostatic waves (Langmuir waves) for

$\vec{B} = 0$ are with high frequencies, the electron plasma frequency ωpe (negligible movement of ions) or low frequencies, the ion plasma frequency ωpi called ion acoustic waves or pseudo-noise waves.

1. The kinetic-fluid hybrid models:

These models use the kinetic approach to manage non-local transport of electrons and ions in discharges and to derive transport coefficients of charged species. The fluid approach is applied simultaneously to achieve the density of charged particles and distribution of electric field. Hybrid models have been developed to simulate fairly complex chemistries of gas discharges. Transport coefficients and reaction rates of electrons with molecules are derived kinetically, while the density of species and the time and spatial variation of the electric field are calculated using the method of fluid flow.

-*The kinetic-MHD* model treats the low-energy core component by MHD description, the energetic component by a kinetic approach such as the gyrokinetic equation, and the coupling between the dynamics of these two components through plasma pressure in the momentum equation [15]. This model is applicable to magnetized collisionless plasma systems where the energetic particle density is small in comparison with the cold core plasma component so that parallel electric field effects are negligibly small.

-*The kinetic-multifluid* model has eliminated high frequency wave phenomena with frequency the order of the electron cyclotron frequency. It is appropriate for studying ion cyclotron wave phenomena for multiple ion species, Alfven and MHD waves [15].

-*The low kinetic-fluid* model eliminates ion cyclotron waves, but is appropriate for studying kinetic effects on MHD phenomena. It is in this regime that the multi-ion fluid model reduces to a one-fluid model [15] (i.e. this model preserves the one-fluid framework, but retains the kinetic effects of multiple ion species).

IIV. Conclusion

The controlled thermonuclear fusion, an energy source adapted to produce electricity on a large scale and whose resources are almost limitless, is part of the main objectives of research in plasma physics. Tokamak is the machine for magnetic confinement is the configuration the most promoters for achieving this controlled reactions. For this effect the efforts are united to build a big tokamak in France, under the ITER project of international collaboration that should constitute the biggest scientific yard of this century.

In this paper, we presented a comparison by analysis of the applicability of both models, fluid (mainly MHD) and kinetic (Vlasov), on concrete problems of plasma physics such as plasma edge and plasma core in a Tokamak and the limits of validity of each model.

The fluid models describe plasmas in terms of macroscopic quantities such as density and average speed around each position, the average energy. They are often accurate when collisionality is sufficiently high to maintain the plasma velocity distribution close to a Maxwell-Boltzmann distribution. This description is appropriate where collisions play an important role as in the plasma edge. This approach is relatively «slight» because only 3D, so it cannot correctly describe several fundamental phenomena in weakly collisional plasmas. So it must be completed by the kinetic one.

Kinetic models describe the distribution function of particle velocity at each point in the plasma, and therefore should not assume a Maxwell-Boltzmann. A kinetic description is often necessary for collisionless plasmas as in the Maxwellian plasma of core of Tokamak, solar corona, the magnetosphere and the solar wind. They are generally more computationally intensive than fluid models.

We concluded that these two models may not be competing but complementary. This gives rise to hybrid models kinetic-fluid.

Nowadays, hybrid models are implemented very often especially in involve molecular gases since they combine the accuracy of kinetic models with short computational times of fluid models.

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Université Kasdi Merbah – Ouargla
Faculté des Sciences et Technologies et des Sciences de la Matière
Laboratoires LENREZA & LRPPS & Département Sciences de la Matière

Séminaire International sur la Physique des Plasmas
International Seminar on Plasma Physics
(SIPP'2011)
Ouargla, du 13 au 15 Février 2011

Programme Scientifique du Séminaire

THÈMES
A – PROPRIETES STATISTIQUES DANS LES PLASMAS
B – ONDES DANS LES PLASMAS
C – LASER ET SPECTROSCOPIE DANS LES PLASMAS
D – PLASMAS DE SURFACES

Journée du 13 Février 2011 :

Réception des participants : 08h00 à 09h00

Session 1 : 09h00 à 10h45 (Cérémonie d'ouverture + Conférence)
- Cérémonie d'ouverture : 09h00 à 09h45
- 1ère Conférence : 09h45 à 10h45

Président de session : *Pr Benamira F.*
Rapporteur : *Pr Liani B.*
- **Conférencier [C1] : *Pr Meftah M.T.***

Titre **: LA RECHERCHE DANS LA PHYSIQUE DES PLASMAS**
Pause café

Session 2 (Thème A) : 11h15 à 12h15 (3 Communications orales)
Président de session : *Pr Kerdja T.*
Rapporteur : *Dr Sabri G.N.*
Communications orales : de oA1 à oA3
Déjeuner

Session 3 (Thème A) : 14h30 à 16h00 (5 Communications orales)
Président de session : *Pr Benmalek M.*
Rapporteur : *Dr Bentabet A.*
Communications orales : de oA4 à oA8
Pause café

Session 4 : 16h00 à 17h30 (Session de POSTERS)
Présentation et discussion des posters : Thèmes A (12) et B (09)

[oA13] PHASE TRANSITIONS AND CATASTROPHES IN ACOUSTOPLASMA

THÈME B : ONDES DANS LES PLASMAS

SABRI N.G. et BENOUAZ T.
[oB1] STUDY OF ELECTRON CYCLOTRON ABSORPTION IN TOKAMAK PLASMA USING KINETIC MODEL

TAHRAOUI A., BELHEOUANE S. et ANNOU R.
[oB2] ONDES SOLITAIRES POUSSIEREUSES DANS UN PLASMA FROID

THÈME C : LASER ET SPECTROSCOPIE DES PLASMAS

ACHOURI M., BABA HAMED T. et BELASRI A.
[oC1] SPECTROSCOPIE DU PLASMA D'ABLATION LASER (LIBS)

AZZOUZI F. et TRIKI H.
[oC2] DYNAMIQUE NON LINEAIRE DE LA PROPAGATION DES SOLITONS LASERS DANS LES MILIEUX DISPERSIFS D'ORDRE SUPERIEUR

BOUDAOUD F., M. LEMERINI et A. HADDOUCHE
[oC3] APPLICATION D'UNE METHODE INTERFEROMETRIQUE POUR LE CALCUL DES PROFILES DE LA DENSITE ET DE LA TEMPERATURE D'UN GAZ SOUMIS A UNE DECHARGE COURONNE

DIFALLAH M., BEDIDA N. et MEFTAH M.T.
[oC4] SUR LA PHASE DE BERRY DANS LA SPECTROSCOPIE DES PLASMAS

FERHAT B., REDON R., RIPERT M., BOIS A. et AZZOUZ Y.
[oC5] PARAMETRES STARK DE QUELQUES RAIES ASYMETRIQUES DE SiII

FEROUANI A.K. et INAL M.
[oC6] DIAGNOSTIC EN TEMPERATURE ELECTRONIQUE DES PLASMAS CHAUDS BASE SUR LES RAIES X

LAFANE S., KERDJA T., ABDELLI-MESSACI S. et S. MALEK S.
[oC7] PLUME EXPANSION DYNAMICS DURING $Sm_{1-X}Nd_XNiO_3$ THIN FILM DEPOSITION

THÈME D : PLASMAS DE SURFACES

AÏSSA A., ABDELOUAHAB M., NOUREDDINE A., EL-GANAOUI M. et PATEYRON B.
[oD1] TRAITEMENT THERMIQUE D'UNE PARTICULE INJECTE DANS UN MILIEU PLASMAGENE

LOUKIL H. et BELASRI A.
[oD2] EFFET DE L'ENERGIE DEPOSEE DANS LE PLASMA HAUTE PRESSION SUR LES CARACTERISTIQUES D'UNE LAMPE A EXCIMER

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oB1

STUDY OF ELECTRON CYCLOTRON ABSORPTION IN TOKAMAK PLASMA USING KINETIC MODEL

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ABSTRACT: Electron-cyclotron (EC) absorption in tokamak plasma. is based on interaction between wave and electron cyclotron movement when the electron passes through a layer of resonance at a fixed frequency and dependent magnetic field. This technique is the principle of additional heating (ECRH) and the generation of non-inductive current drive (ECCD) in modern fusion devices. In this paper we are interested by the problem of EC absorption which used a microscopic description of kinetic theory treatment versus the propagation which using the cold plasma description. The power absorbed depends on the optical depth which in turn depends on coefficient of absorption and the order of the excited harmonic for O-mode or X-mode.

KEYWORDS: electron-cyclotron (EC), absorption, tokamak, plasma, kinetic, resonance, ECRH, mode

1. Introduction:

With respect to the theory, it is very important to have a quantitative model for the way the wave propagates and is absorbed inside the plasma, as well as for the effects the resonant electrons have on the wave. At this effect, in this study we focus more on the absorption which shows important properties using the kinetic model.

The injection of electron-cyclotron (EC) waves is nowadays a well-established method for coupling energy to plasma electrons in modern fusion devices, with primary applications the plasma heating (ECRH) and the generation of non-inductive current drive (ECCD)[1].

At the same time, ECRH and ECCD have shown their importance in tokamak studies and their present usage goes beyond their heating and current drive application. In current fusion experiments, the EC radiation is launched in the plasma in the form of spatially narrow wave beams, and the plasma electrons interact with the ECRH studies are formally split in the experiments involving the injection of EC waves [2] on the one hand, and on the other in the theoretical investigations related to the propagation and absorption of the radiation.

2. Propagation and dispersion relation

To describe the propagation of electron cyclotron waves in plasma is generally used the cold plasma approximation [3]. In this approximation the plasma pressure is assumed very small compared to the pressure magnétique $\beta \ll 1$. In this case the thermal motion of electrons may be negligible in terms of oscillations of the wave $v_\varphi \gg v_{th}$ where v_φ is the phase velocity of the wave and v_{th} is the thermal velocity of electrons and the Larmor radius is small compared to the length wave [4]. The relation between $\vec{j}$ and $\vec{E}$ can be written as

$$\vec{j}(\vec{k},\omega) = \bar{\bar{\sigma}}(\vec{k},\omega).\vec{E}(\vec{k},\omega) \quad (1)$$

Where $\vec{k}$ is the wave vector, $\bar{\bar{\sigma}}$ is the conductivity of the plasma that is a tensor in case of anisotropic plasma. Considering plane wave solutions of Maxwell's equations, such as fluctuating quantities vary as $exp\ (i\ (\vec{k}\,.\vec{r} - \omega t))$. In Fourier space, we can find from the Maxwell's equations a wave equation of the form [5]:

$$k^2\vec{E} - \vec{k}(\vec{k}\vec{E}) - \left(\frac{\omega^2}{c^2}\right)\vec{D} = 0 \quad (2)$$

Where $\vec{D} = \overline{\overline{K}}\vec{E}$ is the electrical induction vector, $\overline{\overline{K}}$ is the dielectric tensor (permittivity), $\vec{D}$ is the vector of wave electric field. In the cold plasma approximation, the dielectric tensor $\overline{\overline{K}}$ can be written in the following matrix form [3], [5]:

$$\overline{\overline{K}} = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix} \tag{3}$$

Where in the field of electron cyclotron wave frequency ($\omega \gg \omega_{ci}, \omega_{pi}$), and $S = 1 - \frac{\omega_{pe}^2}{(\omega^2-\omega_{ce}^2)}$; $D = -i\frac{\omega_{ce}}{\omega}\frac{\omega_{pe}^2}{(\omega^2-\omega_{ce}^2)}$; $P = 1 - \frac{\omega_p^2}{\omega^2}$; $R = 1 - \frac{\omega_p^2}{\omega(\omega+\omega_c)}$ and $L = 1 - \frac{\omega_p^2}{\omega(\omega-\omega_c)}$ with $\omega_{pe}^2 = \frac{4\pi n_e e^2}{m_e}$, $\omega_{ce} = \frac{eB_0}{m_e c}$. Where n_e is the electron density, $-e$ the electron charge and m_e its mass. If the refractive index is written $\vec{N} = \frac{\omega}{c}\vec{k}$, the equation (2) can conduct to resolving the dispersion equation which may take the form :

$$AN^4 + BN^2 + C = 0 \tag{4}$$

With $A = S\sin^2\theta + P\cos^2\theta$, $B = RL\sin^2\theta + PS(1+\cos^2\theta)$ and $C = PRL$.

In the case of propagation perpendicular to magnetic field ($N_{II} = 0$). We obtain two solutions of equation (4) for the refractive index perpendicular, which can be written:

$$N_O^2 = P = 1 - \frac{\omega_p^2}{\omega^2}, \tag{5}$$

$$N_X^2 = \frac{S^2-D^2}{S} = 1 - \frac{\omega_{pe}^2}{\omega^2}\frac{(\omega^2-\omega_{pe}^2)}{(\omega^2-\omega_{pe}^2-\omega_{ce}^2)} \tag{6}$$

These electromagnetic solutions are well known by the names of ordinary mode (O-mode) and extraordinary (X mode) [6].They are sketched on the Figure 2.

2.1. The ordinary mode (O): The electric field is parallel to the confining magnetic field and transverse$(\vec{E} \perp \vec{k})$. This mode does not have any resonance and propagate to $\omega > \omega_{pe}$ because of the cut-off (see Figure 1 and Figure 2).

2.2. The extraordinary mode (X): The electric field is elliptically polarized in the plane perpendicular to $\overrightarrow{B_0}$. This mode has two cuts and two resonances. According to the phase velocity ω/k, there are two modes X, fast (F) and slow (S) as shown in Figure 1. This mode is propagated for $\omega_L < \omega < \omega_{uh}$, evanescent for $\omega_{uh} < \omega < \omega_R$.

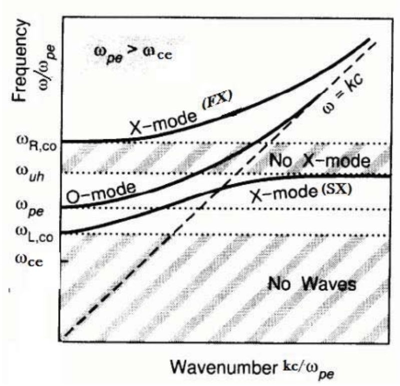

Figure 1: the dispersion diagram

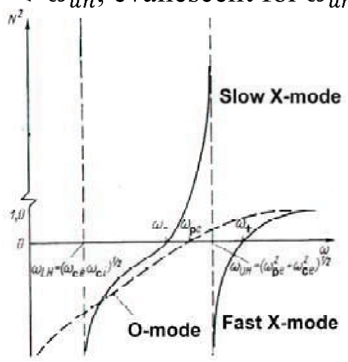

Figure 2: $N^2 = f(\omega)$ for perpendicular propagation

It becomes propagative when $\omega > \omega_R$. With ω_R, ω_L are the cutoff frequencies of the X mode, called right and left, defined by:

$$\omega_{R,L} = \frac{1}{2}\left[\mp\omega_c + \left(\omega_c^2 + 4\omega_p^2\right)^{1/2}\right] \tag{7}$$

The X mode has a resonance cold ($N_\perp \to \infty$), given by:

$$\omega_{uh} = \sqrt{\omega_c^2 + \omega_p^2} \tag{8}$$

This resonance is called upper hybrid (UH), and we see on the CMA diagram that is not available if $\omega > \omega_c$, which corresponds to the case of EC waves injected into TCV from the low field side. There is also a lower hybrid resonance [7], it is well below the electron cyclotron frequency domain and therefore not interfere here.

3. Absorption of electron cyclotron waves (EC) in plasma

In fact, the cyclotron resonance does not appear explicitly in the cold model. For the cyclotron resonance is, in principle, an interaction between the wave and particle motion. In other words, it involves the microscopic structure of the plasma. We shall use the kinetic theory (as opposed to the fluid theory), to accurately reflect the phenomena occurring at the particle scale. The hot plasma model under certain approximations, leads to a new expression of dielectric tensor can be expressed by a correction of the type:

$$\overline{\overline{K}}_{hot} = \overline{\overline{K}}_{cold}(\omega, B_0, n_{e,0}) + \widetilde{K}(\omega, B_0, n_{e,0}, T_{e,0}) \qquad (9)$$

The hot correction $\widetilde{K}$ depends explicitly on the wave vector $\vec{k}$ and the electron temperature at equilibrium, $T_{e,0}$. To calculate the elements of $\overline{\overline{K}}_{hot}$, we start from the relativistic Vlasov equation [1], [2]. The usual phase space $\{\vec{r};\vec{v}\}$ (real space and velocity space), in the relativistic formalism is replaced by $\{\vec{r};\ \vec{p}\}$ (real space and space of the quantities of motion). So the distribution function of electrons is written $f_e(r,p,t)$ with the relation $\vec{p} = m_{e,0}.\gamma.\vec{v}$ where $m_{e,0}$ is the mass of the electron in repose and $\gamma = 1/\sqrt{1-(\mathrm{v}/\mathrm{c})^2}$ [8]. The distribution function is solution of the relativistic Vlasov equation given by :

$$\frac{\partial f_e}{\partial t} + \frac{c^2}{\sqrt{p^2c^2+m_{e,0}^2c^4}}\vec{p}\frac{\partial f_e}{\partial \vec{r}} - e\left(\vec{E} + \frac{c^2}{\sqrt{p^2c^2+m_{e,0}^2c^4}}\vec{p}\wedge\vec{B}\right)\frac{\partial f_e}{\partial \vec{p}} = 0 \qquad (10)$$

In this equation, collisions are neglected because the characteristic time of wave-plasma interaction is much faster than the collision time characteristics.

3.1. Relativistic dielectric tensor

We define the distribution function f_e by the sum of two distribution functions f_{e0} and f_{e1} with zero order (the equilibrium state) and first order (the perturbed state) respectively as follows

$$f_e(\vec{r},\vec{p},t) = f_{e,0}(\vec{p}) + f_{e,1}(\vec{r},\vec{p},t) \qquad (11)$$

Similarly the magnetic and electric fields perturbed [9], written $\vec{B} = \overrightarrow{B_0} + \overrightarrow{B_1}$ and $\vec{E} = 0 + \overrightarrow{E_1}$. A perturbed state the linearized Vlasov equation takes the form

$$\frac{df_{e,1}}{dt} = \frac{\partial f_{e,1}}{\partial t} + \frac{\vec{p}}{m_e}\frac{\partial f_{e,1}}{\partial \vec{r}} + \frac{e}{m_e}\left(\vec{p}\wedge\overrightarrow{B_0}\right)\frac{\partial f_{e,1}}{\partial \vec{p}} = -e\left(\vec{E} + \frac{\vec{p}\wedge\vec{B}_1}{m_e}\right).\frac{\partial f_{e,0}}{\partial \vec{p}} \qquad (12)$$

Where $m_e^2 = m_{e,0}^2 + (p/c)^2 = m_{e,0}^2\gamma^2$ is the relativistic mass of the electron. For relativistic Maxwellian distribution function $f_{e,0}$, the integration of equation (12) give the relativistic dielectric tensor:

$$K_{ij} = \delta_{ij} - \frac{\omega_p^2}{\omega^2}\frac{\mu^2}{2I_2(\mu)}\int_{-\infty}^{+\infty} d\overline{p}_{II}\int_0^{+\infty}\overline{p}_\perp d\overline{p}_\perp \frac{e^{-\mu\gamma}}{\gamma}\sum_{n=-\infty}^{n=\infty}\frac{P_{i,j}^n(p_\perp,p_{II})}{\gamma - n\frac{\omega_{ce}}{\omega} - n_{II}\bar{p}_{II}} \qquad (13)$$

Where $\bar{p} = p/(m_{e,0}c) = \overline{p}_\perp + \overline{p}_{II}$ and $n_{II} = ck_{II}/\omega$ is the index refraction for parallel direction to $\overrightarrow{B_0}$. The sum is over all integers n. With $\mu = mc^2/(k_BT_e) = c^2/v_{th,e}^2$, $v_{th,e}$ is the thermal velocity of electrons, $I_n(z)$ is the modified Bessel function of index n (here $n = 2$) and argument z. For a relatively small approximation we have $f_0 = n_e\left(v_{th,s}\sqrt{\pi}\right)^{-3}e^{\left(-\frac{v^2}{v_{th,e}^2}\right)}$, the relativistic dielectric tensor is given by:

$$\overline{\overline{K}}_{hot} = \begin{pmatrix} S + \widetilde{K}_q(z_n) & -i\left(D + \widetilde{K}_q(z_n)\right) \\ i\left(D + \widetilde{K}_q(z_n)\right) & S + \widetilde{K}_q(z_n) \end{pmatrix} \qquad (14)$$

$$\widetilde{K}_q(z_n) = -\frac{2q-3}{2^{q-1/2}(q-\frac{5}{2})!!}\left(\frac{\omega_p}{\omega_c\omega_c}\right)^2\left(\frac{\omega_p}{\omega_c}\right)^{2q-7}\left(\frac{v_{th,e}}{c}\right)^{2q-7}K_\perp^{2q-5}F_q(z_n) \qquad (15)$$

Where $N_\perp = ck_\perp/\omega$ is the index refraction for perpendicular direction to magnetic field $\vec{B}$ et $F_q(z_n)$ is Dnestrovskij function of index $q = n + 3/2$ defined by :

$$F_q(z_n) = -i\int_0^\infty \frac{d\tau'}{(1-i\tau')^q} e^{iz_n\tau'} \qquad q \in \frac{1}{2}\mathbb{N} \tag{16}$$

And argument

$$z_n = \left(\frac{c}{v_{th,e}}\right)^2 \frac{\omega - n\omega_c}{\omega} \tag{17}$$

If we decompose the dielectric tensor in part Hermitian and anti-Hermitian respectively as $\overline{\overline{K}} = \overline{\overline{K}}_h + i\overline{\overline{K}}_a$. And if one decompose the correction $\widetilde{K}$ in hot real part and imaginary $\widetilde{K} = \widetilde{K}' + i\widetilde{K}''$. The expression (14) can be written:

$$\overline{\overline{K}}_{hot} = \underbrace{\begin{pmatrix} S + \widetilde{K}_q' & -i(D - \widetilde{K}_q') \\ i(D - \widetilde{K}_q') & S + \widetilde{K}_q' \end{pmatrix}}_{hermitian} + i\underbrace{\begin{pmatrix} \widetilde{K}_q'' & i\widetilde{K}_q'' \\ -i\widetilde{K}_q'' & \widetilde{K}_q'' \end{pmatrix}}_{anti-hermitian} \tag{18}$$

It can be shown that the first part Hermitian $\overline{\overline{K}}_h$ characterizes the propagation while the second part of anti-Hermitian $\overline{\overline{K}}_a$ characterized the absorption [4]. If $T_e \to 0$, we obtain $\overline{\overline{K}}_a = 0$ and $\overline{\overline{K}}_h = \overline{\overline{K}}_{cold}$. A final remark is that, generally, we find that $\overline{\overline{K}}_h = \overline{\overline{K}}_{cold}$, which justifies the use of the approximation to describe the cold wave propagation [4].

The relation of resonance is given by the relativistic cyclotron resonance condition as follows:

$$\gamma - k_{II}v_{II} - n\frac{\omega_{ce}}{\omega} = 0 \tag{19}$$

The term $k_{II}v_{II}$ describes longitudinal Doppler effect [8]. The term $n\omega_{ce}/\omega$ describes the gyration of the electron; n is the order of the harmonic excited.

3.2. Absorption coefficient:

We take the viewpoint of geometrical optics by considering a plane monochromatic wave type $\vec{E}(\vec{r}, t) = \vec{E}(\vec{k}, \omega)\, exp\{i[\vec{k}.\vec{r} - \omega t]\}$ for which one trying to describe the dissipation by introducing the concept of absorption coefficient. For there to be absorption, it is necessary that $k = k' + ik_a''$ avec the imaginary part of wave vector $k_a'' = (\omega/c)N'' \neq 0$. Then the absorption coefficient [10] is given by

$$\alpha = -2k_a''.\frac{\vec{v}_g}{v_g} \tag{20}$$

With $\overrightarrow{v_g} = \frac{d\vec{r}}{dt}$ is the group velocity. For the explicit calculation of the absorption coefficient, we introduce another approach based on energy conservation, using the anti-Hermitian part of the dielectric tensor. Poynting's theorem [11] writes:

$$\frac{\partial W_{0,t}}{\partial t} + \vec{\nabla}.\vec{S}_{0,t} = \frac{\partial}{\partial t}\frac{1}{2}\left(\frac{|\vec{B}_t|^2}{\mu_0} + \varepsilon_0|\vec{E}_t|^2\right) + \frac{1}{\mu_0}\vec{\nabla}.Re(\vec{E}_t \wedge \vec{B}_t) = -\vec{j}_t.\vec{E}_t \tag{21}$$

Where $\partial W_{0,t}/\partial t$, The instantaneous energy density contains the magnetic energy $|B_t|^2/(2\mu_0)$ and electrostatic $\frac{1}{2}\varepsilon_0|E_t|^2$. $\vec{S}_{0,t}$ is the instantaneous Poynting vector in vacuum describing the flow of electromagnetic energy. The source term, $-\vec{j}_t.\vec{E}_t$, describes the interactions of the wave with the plasma. By performing the time average over a few periods of oscillations $\langle E_t\rangle t = E_1(\vec{r})\, exp(i\vec{k}.\vec{r})$, and separating explicitly the hermitian and antihermitian parts of dielectric tensor introduced into the source term, we can be extracted from equation (21) the absorption coefficient:

$$\alpha = \frac{\varepsilon_0\omega\overrightarrow{E_1^*}\overline{\overline{K}}_a\overrightarrow{E_1}}{|\vec{S}|} \tag{22}$$

Where $\overrightarrow{E_1^*}$ is the complex conjugate of $\overrightarrow{E_1}$ et $\vec{S} = \vec{S}_0 + \vec{Q}_s$ with $\vec{S}_0 = \frac{1}{4\mu_0}Re(\vec{E}_1^* \wedge \vec{B}_1 + \vec{E}_1 \wedge \vec{B}_1^*)$ and $\vec{Q}_s = -\frac{1}{4}\varepsilon_0\omega\vec{E}_1^*\frac{\partial\overline{\overline{K}}_h}{\partial k}.\vec{E}_1$. A useful quantity is the optical depth τ [2], [12], [13], which is defined as the integral of the absorption coefficient α along the trajectory s of the wave: $\tau = \int -\alpha\, ds$. The total absorbed power P_{abs} in the plasma can then be written as

$$P_{abs} = P_{inj}\,(1 - exp(-\tau)) \tag{23}$$

4. EC absorption in tokamak plasmas:

In current fusion machines, the accessibility conditions usually require to inject the electronic cyclotron waves from low-field side. This imposes constraints on the polarization and the chosen mode from firstly of the propagation characteristics of ordinary and extraordinary modes and secondly from the absorption characteristics. So it is advantageous to use low-order harmonics of the interaction, to maximize absorption. The Figure 4 shows the typical shapes of cut-offs right (ω_R), left (ω_L), and plasma ω_{pe}, the high hybrid resonance ω_{uh} and cyclotron frequency ω_{ce} in the poloidal plane. A very synthetic way to represent this problem of choosing the mode and propagation is the CMA diagram, as is shown on the figure 5, [1].

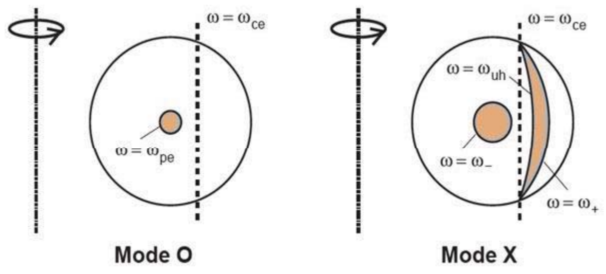

Figure 4 : Typical cuts-off and resonances of a tokamak plasma. Ordinary mode (left) and extraordinary mode (right).

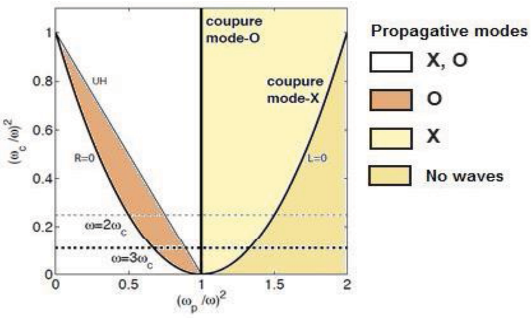

Figure 5: CAM diagram

5. Description of experimental system of EC heating on the TCV tokamak

The EC heating system in TCV [2], is produced by 9 gyrotrons deliver a total power of 4.5MW for a maximum duration of 2s and grouped into three clusters: A, B and C, each consisting of 3 gyrotrons. Two clusters are composed of gyrotrons at a frequency of 82.7 GHz , the second harmonic of the EC frequency, X2. Cluster C is composed of gyrotrons at a frequency of 118 GHz, the third harmonic frequency EC, X3. EC waves are transported to the tokamak by transmission lines formed waveguides vacuum with a length of 30 m and then injected into the plasma by six launchers as is shown in Fig.7.

For maximizing the X3 absorption a top-launch is used implying that absorption strongly depends on the launcher poloidal angle, the plasma density, temperature and injected power.

5.1. Absorption sensitivity properties of X3

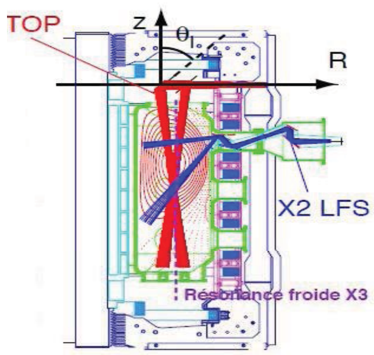

Figure 6: The EC heating system, X2 and X3

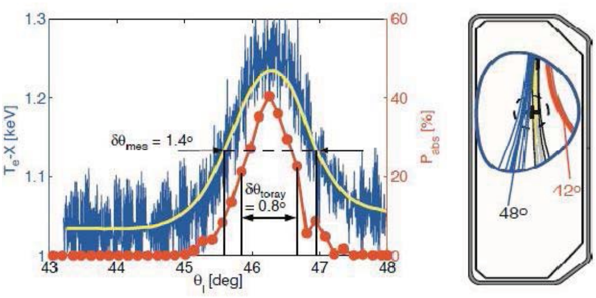

Figure 7: CAM diagram

The following experiments (Dr. G.Arnoux 2005) demonstrating the sensitivity of the X3 absorption on the angle of the mirror θ_l and the dependencies in the density and temperature of the optimum angle, $\theta_{l,opt}$. In these experiments the central density is $n_{e,0} = 5.510^{19} m^{-3}$ and the injected power of X3 is $P_{inj}^{X3} = 450\ kW$ (1 gyrotron). The optimum launcher angle $\theta_{l,opt}$ corresponds to the maximum single pass absorption is experimentally determined by the maximum of Te-X (filtered in yellow curve) on figure 7.

A good agreement is found between experiment and the simulation with TORAY-GA (red dots) which predicts absorption sensitivity such as $\delta\theta_{mes} = 1.4°$, $\delta\theta_{toray} = 0.8°$ which is defined by the FWHM of the smoothed Te-X measurement and of the P_{abs} dotted curve respectively. During the ECH phase, θ_l is swept from 43° to 48° to determine $\theta_{l,opt}$. This scenario is repeated for different central densities: $3.1 \leq n_{e,0} \leq 8.0 . 10^{19}\ m^{-3}$. The absorption calculated by TORAY-GA (•) is superimposed on the temperature measurements.

6. Summary and discussion

The application of EC waves to plasmas rests on a wide base of theoretical work which progressed from simple cold plasma models to hot plasma models with fully relativistic physics to quasilinear kinetic Vlasov models. In this case, all the information about the absorption of the EC wave in the inhomogeneous plasma, is finally expressed in terms of the relativistic dielectric tensor which characterizes the propagation with it Hermitian part and the absorption with it anti-Hermitian one. For a very low electron temperature $T_e \rightarrow 0$, the Hermitian part of the tensor present the cold dielectric tensor which justifies the use of the approximation to describe the cold wave propagation[4].

In order to characterize the X3 absorption properties of X3 top-launch ECH on TCV EC system, a set of experiments has been performed and they have found that maximum X3 absorption strongly depends on the launcher poloidal angle, the plasma density, temperature and injected power. Also, good agreement is found between Simulations using the linear ray-tracing code TORAY-GA are compared to the experimental results.

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The Sharjah International Conference on

Nuclear & renewable Energy

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College of Sciences, University of Sharjah, **3-5 April, 2011**

14/03/2011

Melle Sabri Naima

University of Bechar
Paper Reference Number: NE-166

Dear Colleague,

It is my great pleasure to inform you that your paper entitled "Production of thermonuclear energy by plasma EC heating in tokamak machine" has been **accepted** as an oral presentation at the Sharjah International Conference on Nuclear and renewable Energy, SHJ-NRE11, which will be held on April 3-5, 2011 at the University of Sharjah, Sharjah - United Arab Emirates.

More details about the conference, technical and scientific programs, various events and hotel accommodation can be found in the conference link:
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Should you have any questions, please do not hesitate to contact us.

Yours,

Hussein M Elmehdi, PhD

Coordinator – Scientific Committee
Chair – Organizing Committee

College of Arts & Sciences
University of Sharjah

Production of thermonuclear energy by plasma additional heating systems with electron cyclotron and Alfven waves in tokamak machine

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ABSTRACT

Electron cyclotron (EC) absorption in tokamak plasma is based on interaction between wave and electron cyclotron movement when the electron passes through a layer of resonance at a fixed frequency and dependent magnetic field. This technique is the principle of additional heating (ECRH) and the generation of non-inductive current drive (ECCD) in modern fusion devices. In this paper we are interested by the problem of EC absorption which used a microscopic description of kinetic theory treatment versus the propagation which used the cold plasma description. The power absorbed depends on the optical depth which in turn depends on coefficient of absorption and the order of the excited harmonic for O-mode or X-mode. There is another possibility of heating by dissipation of Alfven waves, based on resonance of cold plasma waves, the shear Alfven wave (SW) and the compressional Alfven wave (FW). Once the (FW) power is coupled to (SW), it stays on the magnetic surface and dissipates there, which is cause the heating of bulk plasmas. This present calculation allows us to compare the two heating systems.

INTRODUCTION

Energy is essential to whole life; is a major scientific and strategic challenge to discover a new method of energy production that has an impact as low as possible on health, and the environment and the overall functioning of the planet, with sufficient energy to several million years. Energy produced from thermonuclear fusion reactions had been known for some decades in the sun and stars, is likely safe and doesn't produce greenhouse gas emissions and its radioactive wastes is less expensive to manage. These reactions require special conditions of temperature (100 million degrees) and pressure. In this case, the more promoter configuration to realize them is tokamak which is a machine governed by Lawson criterion [1], $nTt_E \geq 5.10^{21}\ m^{-3}keVs$ (n density, T temperature and t_E confinement time) and to achieve these high temperatures, it is necessary to heat the plasma.

The ohmic regime is the first natural heating mechanism. Unfortunately, this effect is proportional to the resistance of the plasma which tends to collapse when the temperature increases. We therefore use additional heating systems. Radio-frequency heating (S. Wang[†] and J.Tang, 2004) is one of important of these systems. It is based on the phenomenon of wave-particle resonance where the waves can be transferred their energy to the charged particles in the plasma, which in turn collide with other plasma particles, thus increasing the temperature of the bulk plasma.
The injection of electron-cyclotron (EC) waves is nowadays a well-established method for coupling energy to plasma electrons in modern fusion devices (R.W. HARVEY and al., 1996, P. Mandrin, 1999), with primary applications the plasma heating ECRH (Electron Cyclotron Resonance Heating),(G.Arnoux, 2005) and the generation of non-inductive current drive ECCD (Electron Cyclotron Current Drive), (R. Dumont, 2001, P. Nikkola, 2004).

In this sense, the ECRH studies are formally split in the experiments involving the injection of EC waves on the one hand, and on the other in the theoretical investigations related to the propagation (M. Fontanesi and S. Bernabei , 1971) and absorption (A.Orefice, 1988), of the radiation. With respect to the theory, it is very important to have a quantitative model for the way the wave propagates and is absorbed inside the plasma (M. Bornaciti, 1982), as well as for the effects the resonant electrons have on the wave. The cold plasma model is used to describe the propagation (T.H. Stix, 1962), and the absorption is described with kinetic model (K. G. Rönnmark, 1985).

The Alfvén wave is a fundamental electromagnetic oscillation in magnetically confined plasmas. Alfvén waves can be either excited spontaneously by instabilities or driven by external sources. It is also believed that Alfvén waves play a crucial role in the heating of bulk plasmas in both magnetic fusion devices and the solar corona. The Alfvén waves band are divided into slow shear Alfven wave (SW) (Appert, 1986) and the fast compressional Alfven wave (FW), (R. C. Cross, and J. A. Lehane, 1967).

Heating plasma by resonant absorption of Alfvén waves is a technique that combines low-frequency conventional technology and low cost of installed capacity. The TCA Tokamak, acronym of heating in tokamak Alfven wave. The TCA/Sw refers to the circular section tokamak of CRPP (Center for Research in Plasma Physics, Switzerland) with the main objective is to investigate the possibility of plasma heating by dissipation of Alfven waves (Cheethan 1980, TCA Team 1985, A. D. Chambrier, 1987) and TCA/Br refers to the Brazilian tokamak with Alfvén wave heating (A. G. Elfimov and al. 1995, L. Ruchlto and al, 1994) is the largest machine and the most powerful and best equipped in diagnostics which provided the most detailed results on the spectrum and heating by Alfven waves. Its purpose is to study the excitation and absorption Alfvén waves in plasma (Hasegawa, 1975, 1982), showing the usefulness of these waves in the additional heating.

In this paper, we examine in some depth, two types of plasma additional heating systems in a tokamak machine. The emphasis is on electron cyclotron heating. First, we briefly come back to the main non-collisional heating mechanisms and to the particular features of the quasilinear theory absorption in the electron cyclotron range of frequencies (ECRF). Then, the Alfvén wave heating is covered more briefly. Where applicable, the prospects for ITER are commented.

WAVE PROPAGATION

Cold plasma dispersion

In this approximation the plasma pressure is assumed very small compared to the magnetic pressure $\beta \ll 1$. Where The parameter β represents the ratio of thermal pressure (kinetic) $p = nk_BT$ and the magnetic pressure $B^2/2\mu_0$. With k_B is the Boltzmann constant; T and n are respectively the temperature and the density of electrons. B is the magnetic field and μ_0 the magnetic permeability in vacuum. In this case the thermal motion of electrons may be negligible in terms of oscillations of the wave $v_\varphi \gg v_{th}$ where v_φ is the phase velocity of the wave and v_{th} is the thermal velocity of electrons and the Larmor radius is small compared to the wavelength [5]. The relation between $\vec{j}$ and $\vec{E}$ can be written as

$$\vec{j}(\vec{k},\omega) = \bar{\bar{\sigma}}(\vec{k},\omega).\vec{E}(\vec{k},\omega) \qquad (1)$$

Where $\vec{k}$ is the wave vector, $\bar{\bar{\sigma}}$ is the conductivity of the plasma that is a tensor in case of anisotropic plasma. Considering plane wave solutions of Maxwell's equations, such as fluctuating quantities vary as $exp\ (i\ (\vec{k}\,.\vec{r} - \omega t))$. In Fourier space, we can find from the Maxwell's equations a wave equation of the form [6]:

$$k^2\vec{E} - \vec{k}(\vec{k}\vec{E}) - \left(\frac{\omega^2}{c^2}\right)\vec{D} = 0 \qquad (2)$$

Where $\vec{D} = \bar{\bar{K}}\vec{E}$ is the electrical induction vector, $\bar{\bar{K}}$ is the dielectric tensor (permittivity), $\vec{E}$ is the vector of wave electric field. In the cold plasma approximation, the dielectric tensor $\bar{\bar{K}}$ can be written in the following matrix form [1], [6]:

$$\bar{\bar{K}} = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix} \qquad (3)$$

Where in the domain of electron cyclotron wave frequency $(\omega \gg \omega_{ci}, \omega_{pi})$, S, D and P are given by

$$S = 1 - \frac{\omega_{pe}^2}{(\omega^2 - \omega_{ce}^2)} \qquad (4)$$

$$D = -i\frac{\omega_{ce}}{\omega}\frac{\omega_{pe}^2}{(\omega^2 - \omega_{ce}^2)} \qquad (5)$$

$$P = 1 - \frac{\omega_p^2}{\omega^2} \qquad (6)$$

$$R = 1 - \frac{\omega_p^2}{\omega(\omega + \omega_c)}\,;\, L = 1 - \frac{\omega_p^2}{\omega(\omega - \omega_c)} \qquad (7)$$

With $\omega_{pe}^2 = \frac{4\pi n_e e^2}{m_e}$, $\omega_{ce} = \frac{eB_0}{m_e c}$. Where n_e is the electron density, $-e$ the electron charge and m_e its mass.

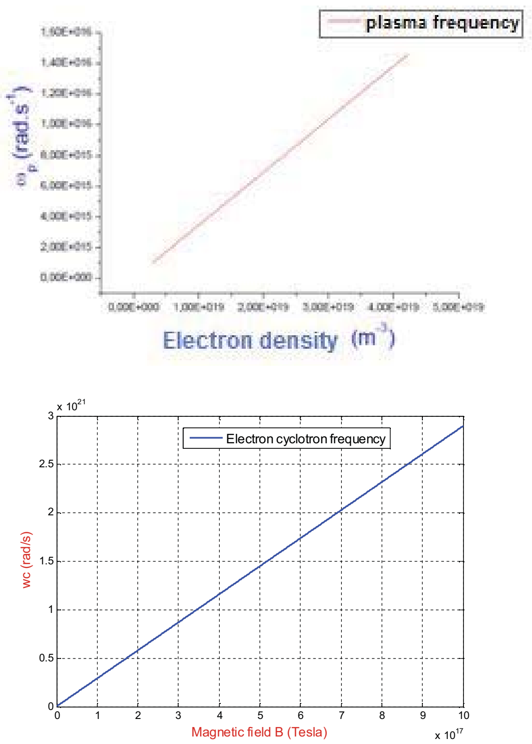

Figure1: (a) the plasma frequency as a function of density and (b) the electron cyclotron frequency as a function of $\vec{B}$.

As the refractive index $\vec{N}$ is written $\vec{N} = \frac{\omega}{c}\vec{k}$; the equation (2) becomes $\bar{\bar{M}}_{k,\omega}\vec{E} = \vec{N}\wedge\vec{N}\wedge\vec{E} + \bar{\bar{K}}.\vec{E} = 0$ and the nontrivial solutions are obtained for: det $(\bar{\bar{M}}_{k,\omega}) = 0$, such as $\bar{\bar{M}}_{k,\omega}$ is a matrix representing the operator $(\vec{k}\wedge\vec{k}\wedge\square +$ ω2c2K.⬚. So we can write:

$$\begin{pmatrix} S - N^2cos^2\theta & -iD & N^2cos^2\theta sin^2\theta \\ iD & S - N^2 & 0 \\ N^2cos^2\theta sin^2\theta & 0 & P - N^2sin^2\theta \end{pmatrix}\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0 \qquad (8)$$

The following system may take the form of the dispersion equation as follows:

$$AN^4 + BN^2 + C = 0 \qquad (9)$$

With $A = Ssin^2\theta + Pcos^2\theta$, $B = RLsin^2\theta + PS(1 + cos^2\theta)$ and $C = PRL$.

To generate current, the power of the electron cyclotron wave must be effectively absorbed by the plasma. However, the quality of the interaction depends on the state of polarization of this wave. It is useful, in this frequency range, using a proper mode (ordinary or extraordinary), chosen according to the plasma conditions, and assume that it propagates up the resonance without modification. In the case of perpendicular propagation to magnetic field $(N_{II} = 0)$. We obtain two solutions of equation (9) for the perpendicular refractive index, which can be written:

$$N_O^2 = P = 1 - \frac{\omega_p^2}{\omega^2}, \qquad (10)$$

$$N_X^2 = \frac{S^2 - D^2}{S} = 1 - \frac{\omega_{pe}^2}{\omega^2}\frac{(\omega^2 - \omega_{pe}^2)}{(\omega^2 - \omega_{pe}^2 - \omega_{ce}^2)} \qquad (11)$$

These electromagnetic solutions are well known by the names of ordinary mode (O-mode) and extraordinary (X mode) [7].

The ordinary mode (O): The electric field is parallel to the confining magnetic field and transverse$(\vec{E} \perp \vec{k})$. This mode does not have any resonance and propagate for $\omega > \omega_{pe}$ because of the cut-off.

The extraordinary mode (X): The electric field is elliptically polarized in the perpendicular plane to $\overrightarrow{B_0}$. This mode has two cut-offs and two resonances. According to the phase velocity ω/k, there are two modes X, fast (F) and slow (S) as it is shown in Figure 2 and in Figure 3. This figure shows the dispersion relations of ordinary (O) and extraordinary (X) fast (F) and slow (S) waves propagating across the magnetic field.

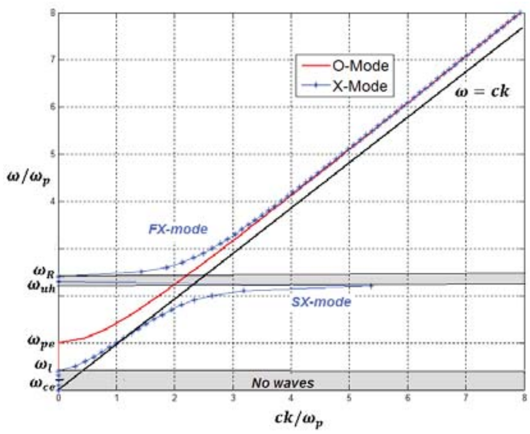

Figure 2: the dispersion diagram

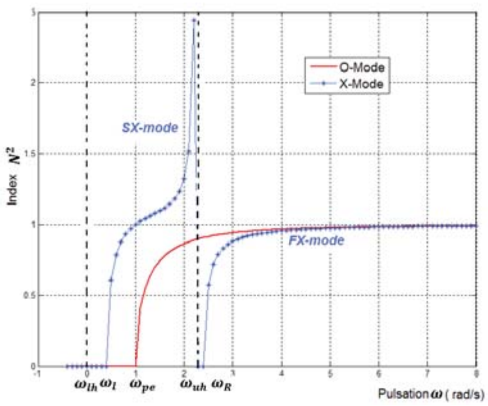

Figure 3: $N^2 = f(\omega)$ for perpendicular propagation

The electron temperature, coupled with their average speed, such as

$$k_\perp \rho_L = N_\perp n \sqrt{k_B T_e/(m_e c^2)} \qquad (12)$$

Where $N_\perp = k_\perp c/\omega$ is the refractive index of the wave in plasma. The two branches of propagation (ordinary and extraordinary) appear and we can see that the ordinary mode propagates for frequencies such that $\omega > \omega_{pe}$. The extraordinary mode is propagative for $\omega_L < \omega < \omega_{uh}$, evanescent for $\omega_{uh} < \omega < \omega_R$. It becomes propagative when $\omega > \omega_R$. With ω_R, ω_L are the cutoff frequencies of the X mode, called right and left modes, defined by:

$$\omega_{R,L} = \frac{1}{2}\left[\mp\omega_c + \left(\omega_c^2 + 4\omega_p^2\right)^{1/2}\right] \qquad (13)$$

The X mode has a cold resonance ($N_\perp \to \infty$), given by:

$$\omega_{uh} = \sqrt{\omega_c^2 + \omega_p^2} \qquad (14)$$

This resonance is called upper hybrid (UH) is not available if $\omega > \omega_c$. There is also a lower hybrid resonance [8], it is well below the electron cyclotron frequency domain and therefore not interfere here.

Electron Cyclotron Wave Absorption

The cyclotron resonance is, in principle, an interaction between the wave and particle motion (see Figure 4).

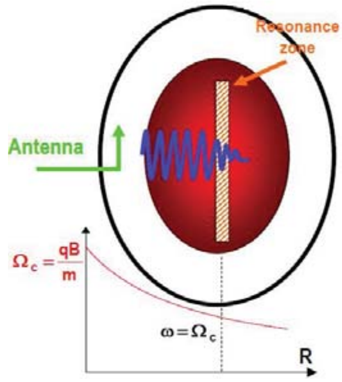

Figure 4: principle of EC heating

In other words, it involves the microscopic structure of the plasma. We shall use the kinetic theory (as opposed to the fluid theory), to accurately reflect the phenomena occurring at the particle scale.

The hot plasma model under certain approximations, leads to a new expression of dielectric tensor that can be expressed by a correction of the type:

$$\overline{\overline{K}}_{hot} = \overline{\overline{K}}_{cold}(\omega, B_0, n_{e,0}) + \widetilde{K}(\omega, B_0, n_{e,0}, T_{e,0}) \qquad (15)$$

The hot correction $\widetilde{K}$ depends explicitly on the wave vector $\vec{k}$ and the electron temperature at equilibrium, $T_{e,0}$. To calculate the elements of $\overline{\overline{K}}_{hot}$, we start from the relativistic Vlasov equation [2], [3].

In the relativistic formalism, the distribution function of electrons is written as $f_e(\vec{r}, \vec{p}, t)$ with the relation $\vec{p} = m_{e,0}.\gamma.\vec{v}$ where $m_{e,0}$ is rest mass. The distribution function is solution of the relativistic Vlasov equation given by:

$$\frac{\partial f_e}{\partial t} + \frac{\vec{p}}{m_e\gamma}\frac{\partial f_e}{\partial \vec{r}} - e\left(\vec{E} + \frac{1}{m_e\gamma}\vec{p} \wedge \vec{B}\right)\frac{\partial f_e}{\partial \vec{p}} = 0 \qquad (16)$$

Where $m_e^2 = m_{e,0}^2 + (p/c)^2 = m_{e,0}^2\gamma^2$ is the relativistic mass of the electron and $\gamma = 1/\sqrt{1 - (v/c)^2}$ [9], the relativistic Lorentz factor, $\gamma = 1$ for a non-relativistic plasma. The distribution function f_e is written as $f_e(\vec{r}, \vec{p}, t) = f_{e,0}(\vec{p}) + f_{e,1}(\vec{r}, \vec{p}, t)$ the sum of two distribution functions f_{e0} for equilibrium state and f_{e1} for the perturbed state. Similarly to distribution function f_e, the magnetic and electric fields [10], can be written as $\vec{B} = \overrightarrow{B_0} + \overrightarrow{B_1}$ and $\vec{E} = 0 + \overrightarrow{E_1}$. A perturbed state of linearized Vlasov equation takes the form

$$\frac{\partial f_{e,1}}{\partial t} + \frac{\vec{p}}{m_e}\frac{\partial f_{e,1}}{\partial \vec{r}} + \frac{e}{m_e}\left(\vec{p} \wedge \overrightarrow{B_0}\right)\frac{\partial f_{e,1}}{\partial \vec{p}} = -e\left(\vec{E} + \frac{\vec{p}\wedge\overrightarrow{B_1}}{m_e}\right).\frac{\partial f_{e,0}}{\partial \vec{p}} \quad (17)$$

The integration of equation (17) gives the relativistic dielectric tensor:

$$K_{ij} = \delta_{ij} - \frac{\omega_p^2}{\omega^2}\frac{\mu^2}{2k_2(\mu)}\int_{-\infty}^{+\infty} d\bar{p}_{II}\int_0^{+\infty} \bar{p}_\perp d\bar{p}_\perp \frac{e^{-\mu\gamma}}{\gamma} U \quad (18)$$

$$U = \sum_{n=-\infty}^{n=\infty} \frac{P_{i,j}^n(p_\perp, p_{II})}{\gamma - n\frac{\omega_{ce}}{\omega} - n_{II}\bar{p}_{II}} \quad (19)$$

Where $\bar{p} = p/(m_{e,0}c)=\bar{p}_\perp + \bar{p}_{II}$, $n_{II} = ck_{II}/\omega$ is the index refraction for parallel direction to $\overrightarrow{B_0}$ and $k_n(z)$ is the modified Bessel function of second kind (or McDonald function) of index n (here $n = 2$) and argument z.

If we decompose respectively the dielectric tensor in hermitian and anti-hermitian parts as $\overline{\overline{K}} = \overline{\overline{K}}_h + i\overline{\overline{K}}_a$. And if one decompose the hot correction $\boldsymbol{K}$ in real and imaginary part as $\widetilde{K} = \widetilde{K}' + i\widetilde{K}"$. The expression (15) can be written:

$$\overline{\overline{K}}_{hot} = \underbrace{\begin{pmatrix} S + \widetilde{K}_q' & -i(D - \widetilde{K}_q') \\ i(D - \widetilde{K}_q') & S + \widetilde{K}_q' \end{pmatrix}}_{hermitian} + i\underbrace{\begin{pmatrix} \widetilde{K}_q" & i\widetilde{K}_q" \\ -i\widetilde{K}_q" & \widetilde{K}_q" \end{pmatrix}}_{anti-hermitian} \quad (20)$$

It can be shown that the first hermitian part $\overline{\overline{K}}_h$ characterizes the propagation while the second anti-hermitian part $\overline{\overline{K}}_a$ characterizes the absorption [8]. If $T_e \to 0$, we obtain $\overline{\overline{K}}_a = 0$ and $\overline{\overline{K}}_h = \overline{\overline{K}}_{cold}$; which justifies the use of the cold approximation to describe wave propagation [11].

The relation of relativistic resonance:

The relation of resonance is given by the relativistic resonance condition as follows:

$$\gamma - k_{II}v_{II} - n\frac{\omega_{c,0}}{\omega} = 0 \quad (21)$$

The term $k_{II}v_{II}$ describes longitudinal Doppler shift [9], ($k_{II} \neq 0$). The term $n\omega_{ce}/\omega$ describes the gyration of the electron; n is the order of the harmonic excited. This relation expresses the equality between the frequency of the wave and the relativistic cyclotron frequency of rotation corrected by the Doppler shift which caused by the electron parallel velocity. The energy of resonant electrons at ω_{ce} and given n_{II}can be written as:

$$E = m_e c^2 (k_{II}v_{II} + n\frac{\omega_{ce}}{\omega} - 1) \quad (22)$$

An increase of the electron parallel velocity of the quantity Δv_{II} translates into a gain in elementary current $\Delta j = -e\Delta v_{II}$. Energy expense is increased by the electron $\Delta E = m_e.v_{II}.\Delta v_{II}$. So we deduce

$$\Delta j = e\frac{\Delta E}{me.v_{II}} \quad (23)$$

This relation translates the generation of electron cyclotron current drive (ECCD) which is an important tool for current profile shaping in magnetically confined plasmas, thanks to the highly localized power deposition of the EC wave and the ease of external control of its deposition location.

Absorption coefficient

We take the viewpoint of geometrical optics by considering a plane monochromatic wave type $\vec{E}(\vec{r},t) = \vec{E}(\vec{k},\omega)\, exp\{i[\vec{k}.\vec{r} - \omega t]\}$ for which one trying to describe the dissipation by introducing the concept of absorption coefficient. For there to be absorption, it is necessary that $k = k' + ik_a''$ avec the imaginary part of wave vector $k_a'' = (\omega/c)N'' \neq 0$. Then the absorption coefficient [12], [13] is given by

$$\alpha = -2k_a''.\frac{\vec{v}_g}{v_g} \quad (24)$$

With $\overrightarrow{v_g} = \frac{d\vec{r}}{dt}$ is the group velocity

For the explicit calculation of the absorption coefficient, we introduce a Another approach based on energy conservation, using the anti-Hermitian part of the dielectric tensor. Poynting's theorem [14] writes:

$$\frac{\partial W_{0,t}}{\partial t} + \vec{\nabla}.\vec{S}_{0,t} = \frac{\partial}{\partial t}\frac{1}{2}\left(\frac{|\vec{B}_t|^2}{\mu_0} + \varepsilon_0|\vec{E}_t|^2\right) + \frac{1}{\mu_0}\vec{\nabla}.Re\left(\vec{E}_t \wedge \vec{B}_t\right) = -\vec{J}_t.\vec{E}_t$$
(25)

$\partial W_{0,t}/\partial t$, contains respectively the magnetic $|B_t|^2/(2\mu_0)$ and electrostatic $\frac{1}{2}\varepsilon_0|E_t|^2$ energies. $\vec{S}_{0,t}$ is the instantaneous Poynting vector in vacuum describing the flow of electromagnetic energy. The source term, $-\vec{J}_t.\vec{E}_t$, describes the interactions of the wave with the plasma. By performing the time average over a few periods of oscillations: $\langle E_t\rangle t = E_1(\vec{r})\, exp(i\vec{k}.\vec{r})$, and separating explicitly the parties hermitian and antihermitienne of dielectric tensor introduced into the source term, we can be extracted from equation (25) the absorption coefficient:

$$\alpha = \frac{\varepsilon_0\omega\overrightarrow{E_1^*}\overline{\overline{K}}_a\overrightarrow{E_1}}{|\vec{S}|} \quad (26)$$

Where $\overrightarrow{E_1^*}$ is the complex conjugate of $\overrightarrow{E_1}$ and $\vec{S} = \vec{S}_0 + \vec{Q}_s$ with

$$\vec{S}_0 = \frac{1}{4\mu_0}Re\left(\vec{E}_1^* \wedge \vec{B}_1 + \vec{E}_1 \wedge \vec{B}_1^*\right) \quad (27)$$

$$\vec{Q}_s = -\frac{1}{4}\varepsilon_0\omega\vec{E}_1^*\frac{\partial\overline{\overline{K}}_h}{\partial k}.\vec{E}_1 \quad (28)$$

And for wave polarized in X-mode, the absorbed power density is given by the numerator of (26) as:

$$\text{Ŋ} = \varepsilon_0\omega\overrightarrow{E_1^*}\overline{\overline{K}}_a\overrightarrow{E_1} = \alpha|\vec{S}| \quad (29)$$

A useful quantity is the optical depth τ [2], [15], [16], which is defined as the integral of the absorption coefficient α along the trajectory s of the wave: $\tau = \int -\alpha\, ds$. The total absorbed power P_{abs} in the plasma can then be written as

$$P_{abs} = P_{inj}\,(1 - exp(-\tau)) \quad (30)$$

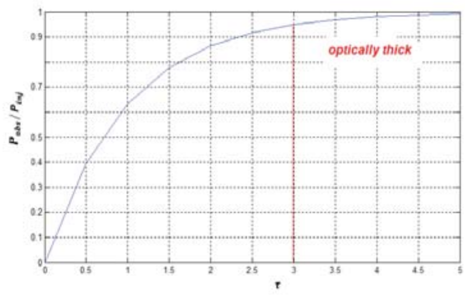

Figure 5: the fraction of absorbed power as a function of optical depth $\boldsymbol{\tau}$, (cas $\boldsymbol{\tau} > 3$) [2].

We can see an illustration of the function P_{abs}/P_{inj} on the Figure 5 where we define that the plasma is optically thick when $\tau > 3$, i.e. when the fraction of absorbed power $P_{abs}/P_{inj} > 95\%$.

Table 1 present the optical depths of a plasma slab in which the magnetic field varies as $B \sim 1/R$ and we obtained:

1- For the O-mode, the optical depth is given for perpendicular propagation and for all harmonics $n \geq 1$.

2- Similarly for the X-mode and the harmonics $n \geq 2$.

3- The optical depth for the fundamental harmonic $n = 1$ of the X-mode is given for oblique propagation.

Table 1 : The optical depth of EC waves [15]

mode	expression
O-mode-⊥ $n \geq 1$	$\tau = \frac{\pi^2 n^{2(n-1)}}{2^{n-1}(n-1)!} N_O^{2n-1} \left(\frac{\omega_p}{\omega_c}\right)^2 \left(\frac{v_t}{c}\right)^{2n} \frac{R}{\lambda}$
X-mode-⊥ $n \geq 2$	$\tau = \frac{\pi^2 n^{2(n-1)}}{2^{n-1}(n-1)!} A_n \left(\frac{\omega_p}{\omega_c}\right)^2 \left(\frac{v_t}{c}\right)^{2(n-1)} \frac{R}{\lambda}$ With $A_n = N_X^{2n-3}\left(1 + \frac{\left(\frac{\omega_p}{\omega_c}\right)^2}{n(n^2-1-\omega_p^2/\omega_c^2)}\right)$
X-mode oblique $n = 1$	$\tau = \pi^2 N_X^5 \left(1 + \frac{\omega_p}{\omega_c}\right)^2 \left(\frac{\omega_c}{\omega_p}\right)^2 \left(\frac{v_t}{c}\right)^2 cos^2\theta \frac{R}{\lambda}$

In the table, $v_{th} = (k_B T_e/m_e)^{1/2}$ is the thermal velocity of the electrons. In most current ECRH tokamak experiments either the fundamental O-mode or second harmonic X-mode are employed. Except near the edges of the plasma, optical depths of the order of one or significantly larger are generally achieved for both the fundamental O- and second harmonic X-mode resulting in complete single pass absorption.

Electron cyclotron absorption in tokamak plasmas

In current fusion machines, the accessibility conditions usually require to inject the electronic cyclotron waves from low-field side. This imposes constraints on the polarization and the chosen mode from firstly of the propagation characteristics of ordinary and extraordinary modes and secondly from the absorption characteristics. So it is advantageous to use low-order harmonics of the interaction, to maximize absorption.

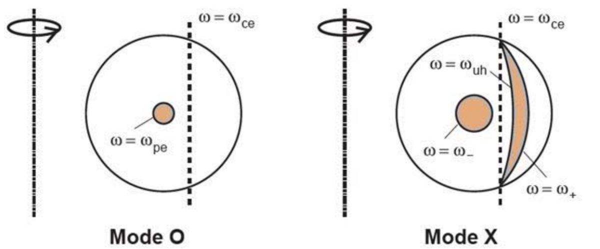

Figure 6: Typical cuts-off and resonances of a tokamak plasma in the case of perpendicular injection from the low-field side. Ordinary mode (left) and extraordinary mode (right).

The Figure 6 shows the typical shapes of cut-offs right (ω_R), left (ω_L), and cut-off plasma ω_{pe}, the high hybrid resonance ω_{uh} and cyclotron frequency ω_{ce} in the poloidal plane. A very synthetic way to represent this problem of choosing the mode and propagation is the CMA diagram, as is shown on the Figure 7, [3].

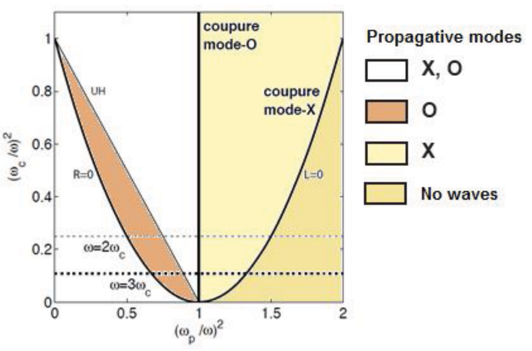

Figure. 7: CAM diagram

Alfven Waves Heating

Alfven waves dispersion

Branches of dispersion oblique propagation have a complicated expression because the continuation between θ = π / 2 and θ = 0. In this case the wave propagates with a low frequency approximation checking the magnetohydrodynamic (MHD) $\omega \ll \omega_{ci}, \omega_{pi}$. The elements of dielectric tensor are given by:

$$S = 1 + \frac{\omega_{pi}^2}{\omega_{ci}^2 - \omega^2} + \frac{\omega_{pe}^2}{\omega_{pe}^2 - \omega^2} \approx 1 + \frac{\omega_{pi}^2}{\omega_{ci}^2} = 1 + \frac{c^2}{v_a^2} \quad (31)$$

$$D \approx \frac{i\omega}{\omega_{ci}} \frac{c^2}{v_a^2} \approx 0 \quad (32)$$

$$P \approx 1 - \frac{\omega_{pi}^2 + \omega_{pe}^2}{\omega^2} \approx 1 - \frac{c^2}{v_a^2} \frac{\omega_{ci}\omega_{ce}}{\omega^2} \approx -\frac{\omega_{pe}^2}{\omega^2} \gg 1$$

$$P \to \infty \quad (33)$$

Here, we used the quasi-neutral plasma, which is written $\omega_{pe}^2/\omega_{ce} = -\omega_{pi}^2/\omega_{ci}$ and the system of eigenvalues (8) reduces to

$$\begin{cases} \left(-n^2 cos^2\theta + 1 + \frac{c^2}{v_a^2}\right) \mathrm{E_x} = 0 \\ \left(-n^2 + 1 + \frac{c^2}{v_a^2}\right) \mathrm{E_y} = 0 \\ (\infty) E_z = 0 \end{cases} \quad (34)$$

Shear Alfven wave (Torsional Alfven wave):

The first equation of system (34) gives the dispersion relation

$$n^2 cos^2\theta = 1 + \frac{c^2}{v_a^2} \quad (35)$$

It is fairly easy to show, from the definitions of the plasma and cyclotron frequencies that $\frac{\omega_{pi}^2}{\omega_{ci}^2} = \frac{c^2}{v_a^2}$. Here, $\rho \simeq nm_i$ is the plasma mass density, and

$$v_a = \sqrt{\frac{B_0^2}{\mu_0 \rho}} \quad (36)$$

is called the *Alfven velocity.* Thus, the dispersion relations of the two low-frequency waves can be written

$$\omega \approx k v_a cos\theta \equiv k_{II} v_a \qquad (37)$$

With a phase velocity

$$v_\varphi \approx v_a^2 cos^2\theta \qquad (38)$$

It is interesting to note that the magnetic perturbation induces torsion of field lines and is therefore called *slow* or *shear* Alfvén wave [17], [18]; see Figure 8.

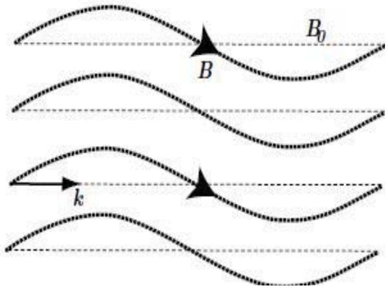

Figure 8: Magnetic field perturbation associated with a shear-Alfven wave

Compressional Alfven wave

The second solution of system (34) gives the dispersion relation

$$n^2 = 1 + \frac{c^2}{v_a^2} \qquad (39)$$

Thus, the dispersion relations of the two low-frequency waves can be written

$$\omega = \frac{k v_a}{\sqrt{1+v_a^2/c^2}} \approx k v_a \qquad (40)$$

With a phase velocity

$$v_\varphi \approx \frac{c}{\sqrt{1+c^2/v_a^2}} = v_a \qquad (41)$$

Figure 9 shows the characteristic distortion of the magnetic field associated with a compressional-Alfvén wave propagating perpendicular to the equilibrium field. Clearly, this wave compresses magnetic field-lines without bending them and this mode is usually called the *fast* or *compressional* Alfven wave also ion magnetosonic wave [17], [18].

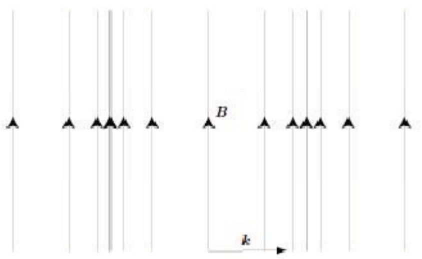

Figure 9: Magnetic field perturbation associated with a compressional Alfén-wave.

Principle of Alfven waves heating

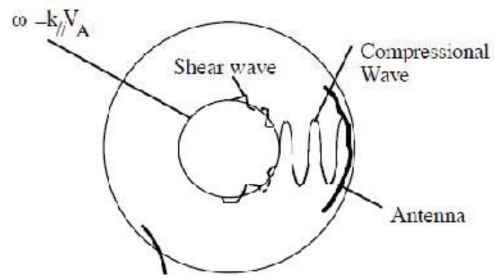

Figure 10: The principle of Alfven wave heating. Poloïdal cross-section of the tokamak [4], [19].

The dispersion relation (35) implies that the shear Alfvén wave can propagate only along the field lines and in an inhomogeneous plasma there is only one surface, close to a magnetic surface, where for a given $N_{//}$ this wave dispersion relation is satisfied. So, the shear Alfvén wave can propagate only on that surface, as shown on Figure 10, it is trapped on that surface.

Therefore, the idea is to launch from the outside the compressional Alfvén wave, which can propagate in all directions and reach the Alfvén resonance. Once the power is coupled to the shear wave by resonance absorption, it stays on the magnetic surface and dissipates there. The Figure 11 shows a schematic diagram of heating by the shear Alfvén wave resonance whose condition is

$$\omega^2(r) = \frac{k_{II}^2 {v_a}^2}{1+k_{II}^2 v_a^2/\omega_{ci}^2} \qquad (42)$$

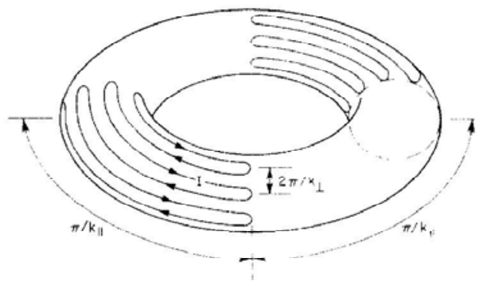

Figure 11: Schematic diagram of the proposed setting of heating coil using shear Alfvèn wave resonance [21].

Note that the wavelength of the compressional wave is of the order of 1m. This means that, for 1m wide or narrower antennas, most of the wave spectrum will be evanescent with an evanescence length of the order of the antenna size [15].

The inclusion of kinetic effects, such as electron and ion temperatures and finite electronic mass, changes the physical picture of processes. This gives rise to an electrostatic wave which propagates in radial direction close to resonant surface of (SW) that called kinetic Alfvèn wave [20]. In this case, the dissipation of the waves is attributed to Landau damping on electrons [21].

From the experimental point of view the most extensive experiments and analysis of Alfven wave heating have been performed on the TCA tokamak [20].

SUMMARY AND DISCUSSION

The application of EC waves to plasmas rests on a wide base of theoretical work which progressed from simple cold plasma models to hot plasma models with fully relativistic physics to quasilinear kinetic Vlasov models. In this case, all the information about the absorption of the EC wave in the inhomogeneous plasma, is finally expressed in terms of the relativistic dielectric tensor which characterizes the propagation with it hermitian part and the absorption with it anti-hermitian one. For a very low electron temperature $T_e \to 0$, the hermitian part of the tensor present the cold dielectric tensor which justifies the use of the cold plasma approximation to describe the wave propagation.

We generally use the cold plasma model to study Alfvén waves and especially to describe the damping of the compressional wave by local absorption of power at the position of the shear Alfvén wave resonance.

Although antenna coupling and general Alfvèn wave behavior appeared to be in agreement with the theory, generally speaking little plasma heating was observed while the main effect of the RF was a large density increase, sometimes interpreted as an increase in the particle confinement time. In view of these disappointing results there have been few attempts to apply Alfven wave heating to large tokamaks and this method is usually not mentioned for the heating of ITER or reactors. However, there has been some renewed interest in this field as the conversion to the kinetic Alfven wave may induce poloïdal shear flows, and possibly to generate transport Barriers [20].

In constract, electron cyclotron (EC) power has technological and physics advantages for heating and current drive (CD) in a tokamak reactor, and advances in source development make it credible for applications in the International Thermonuclear Experimental Reactor (ITER). Because this heating system (ECH) is a particularly *robust* heating scheme since the physics of wave propagation and absorption is well understood, there is total absorption for all plasma parameters foreseen in ITER.

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Title:

Study of energy transfer by electron cyclotron resonance in tokamak plasma

Authors & affiliations:

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[1]*University of Bechar, B.P417 Bechar 08000, Algeria.* [2]*University of Tlemcen 13000, Algeria,*
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Abstract: Your abstract should include one Figure or one Table, and 2 References. It must ALL fit in this box on ONE Page.

Energy is essential to all life, is a major scientific challenge and strategic than discovering new method of energy production that has an impact as low as possible on health and the environment and the overall functioning of the planet with sufficient energy to several million years. Is energy produced from thermonuclear fusion reactions that we are discussing [1]. The production of electrical energy from these reactions is a crucial issue for the future of humanity. Indeed, energy needs continue to grow over the coming decades, while fossil fuel resources (oil, coal, natural gas,..) tend to exhaustion. In addition, energy produced by carbon dioxide will decline because of their emissions. Classical nuclear energy doesn't produce greenhouse gas emissions, but the production of radioactives wastes of long life is a serious problem. Cons thermonuclear fusion is likely safe and don't produces greenhouse gas emissions and its radioactives wastes is less expensive to manage.

The energy of thermonuclear fusion had been known for some decades in the sun and stars. The principle of fusion is to collide light atoms with each other to produce heavier while releasing energy under special conditions of temperature (100 million degrees) and pressure.

To this purpose, efforts are unified in the framework of a large international research program for the construction of a tokamak reactor. This project named ITER began in 2005 in Cadarache (southern France), whose objective: To create an artificial star on earth, producing electricity from fusion energy.

The energy transfer between radio waves and plasma is based on the phenomenon of wave-particle resonance. In particular, one can use a wave resonant with the cyclotron motion of electrons in the plasma is the principle of heating by electron cyclotron resonance ECR plasma in a tokamak [2], as shown in Figure 1.

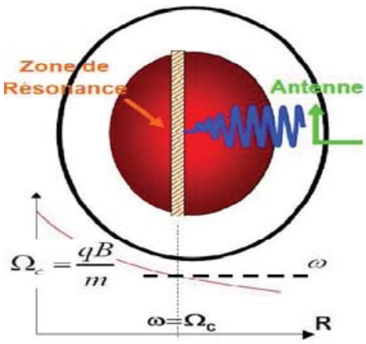

Figure 1 : Principle of ECR heating

The resonance condition written:

$$\gamma - \frac{\omega_c}{\omega} - k_{II} v_{II} = 0 \qquad (1)$$

Where ω the wave frequency, ω_c the cyclotron frequency, k_{II} the projection of wave vector along the direction parallel, v_{II} the electron velocity along the field line. Which finally resulted $\omega = n\omega_c$. This means that the wave absorption in electron cyclotron resonance is one of the best mechanisms for heating in a tokamak.

Keywords: wave, cyclotron, resonance, electron heating, plasma, tokamak.

Reference:

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Study of Radiometry of Electron Cyclotron Emission (ECE) in Tokamak Plasma

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Abstract-
In tokamak plasma, the electrons are confined by total helicoidal magnetic field and they are subject to Lorentz's force which allows them to gyrate around the field lines. These gyrating electrons emit electromagnetic radiations known as electron cyclotron emission ECE at the cyclotron resonance frequency and its harmonics. These frequencies fall in the millimeter wave region of electromagnetic spectrum. Radiometry of electron cyclotron emission (ECE) can be used to determine the electron temperature of the plasma. The use of a multichannel heterodyne radiometers provides an optimum combination of good temporal and frequency resolution, low noise and excellent sensitivity.

Radiofrequency (RF) antenna systems that excite compressional Alfven or "fast" waves, typically operating in the frequency range of 10-120 MHz, are used for both cyclotron magnetic resonance heating of ions and non-resonant heating of electrons. In addition to heating plasmas to the high internal temperatures needed to initiate fusion reactions, RF waves can be used to drive plasma currents, tailor internal pressure profiles, improve energy confinement, and stabilize plasmas. RF systems on present major U.S. experiments are capable of supplying 3-6 MW of power to their plasmas; future reactors such as ITER may need an order of magnitude more power.

Keyswords:

Radiations; electron cyclotron emission ECE; Radiometry; resonance heating.

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Président de la Société Française du Vide

STUDY OF ELECTRON CYCLOTRON CURRENT DRIVE AND HEATING IN TOKAMAK PLASMA

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ABTRACT
To describe the propagation of electron cyclotron waves in plasma is generally used the cold plasma approximation [4]. In this approximation the plasma pressure is assumed very small compared to the magnetic pressure $\beta \ll 1$. In the case of perpendicular propagation to magnetic field ($N_{II} = 0$), we obtain two mode of propagation: the ordinary mode (O-mode) and the extraordinary mode (X mode) [1] as is shown on the figure 1.

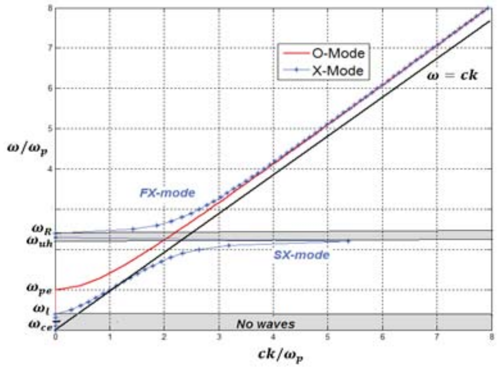

Fig 1. The dispersion diagram of O and X modes.

Electron-cyclotron (EC) absorption in tokamak plasma. is based on interaction between wave and electron cyclotron movement when the electron passes through a layer of resonance at a fixed frequency and dependent magnetic field. This technique is the principle of additional heating (ECRH) and the generation of non-inductive current drive (ECCD) in modern fusion devices. In this paper we are interested by two methods of EC current drive. The first one base on the resonance condition, when particles travelling in one direction around the torus and the second one use the principle of particle trapping. These methods are classed under the global heading of "noninductive current drive», generally, though not exclusively, employing the injection of waves and/or toroidally directed particle beams. An increase of the electron parallel velocity of the quantity Δv_{II} translates into a gain in elementary current $\Delta j = -e\Delta v_{II}$. Energy expense is increased by the electron $\Delta E = m_e . v_{II} . \Delta v_{II}$. The relation $\Delta j = e\frac{\Delta E}{me.v_{II}}$ translates the generation of electron cyclotron current drive (ECCD) which is an important tool for current profile shaping in magnetically confined plasmas, thanks to the highly localized power deposition of the EC wave and the ease of external control of its deposition location.

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Communications Nationales

Study of Alfvèn Waves Properties and its Role in Additional Heating of Tokamak Plasma

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Abstract — **In this paper we tend to study Alfven waves in magnetized cold plasma, where the solution of the global dispersion equation gives two types of Alfven waves along the direction propagation to the magnetic field (between θ = 0 and θ = π / 2) called Shear Alfven wave and Compressional Alfvén wave respectively. Heating plasma by resonant absorption of Alfvén waves is a heating technology with low-frequency for additional plasma tokamak including the TCA (acronym of heating in tokamak Alfven wave) which was built for this goal.**

Keywords — **Alfven waves, cold plasma, compressional Alfvén wave, shear Alfven wave, tokamak , TCA.**

I. Introduction

In this paper, we present the study of Alfvén wave's properties which are waves of magnetohydrodynamic origin resulting from coupling between the magnetic field and velocity field. They have the property to be transverse magnetic field and propagate with a speed proportional to the external magnetic field. It is a simple solution of the MHD system equations. These waves occur in many astrophysical and geophysical. Its domain of validity is that of large scale with low frequencies like physics of stellar winds and solar physics domains.

These waves also play an important role in the additional heating in tokamak plasmas including the machine TCA that works since 1980 and its main objective is the study of heating by Alfven waves AWH.

II. Maxwell's equation

In plasma, it is described by Maxwell's equation of which it we write under the shape:

$$\vec{\nabla}.\vec{D} = \rho_{ext} \quad (1)$$

$$\vec{\nabla}.\vec{B} = 0 \quad (2)$$

$$\vec{\nabla}\Lambda\vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3)$$

$$\vec{\nabla}\Lambda\vec{H} = \vec{j}_{ext} + \frac{\partial \vec{D}}{\partial t} \quad (4)$$

III. Equation of propagation and dispersion relation in cold plasma

The equation of propagation of an electromagnetic wave (varying as $expi(\vec{k}\vec{r} - t.\omega)$) in a collisional plasma [6] ensues of Maxwell's equation and it is expressed by the relation:

$$\vec{k}\Lambda\vec{k}\Lambda\vec{E} + \frac{\omega^2}{c^2}\overline{\overline{K}}.\vec{E} = \vec{0} \quad (5)$$

Where $\overline{\overline{K}}$ is a cold dielectric tensor of plasma such as:

$$\overline{\overline{K}} = \overline{\overline{I}} + \frac{i\overline{\overline{\sigma}}}{\varepsilon_0 \omega} \quad (6)$$

$\overline{\overline{\sigma}}$ is the tensor of conductivity of plasma, $\overline{\overline{I}}$ is the tensor identity. It can write also as:

$$\overline{\overline{K}} = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix} \quad (7)$$

Where S, D and P are the ratings given by Stix

$$S = 1 - \sum_s \frac{\omega_{ps}^2}{(\omega^2 - \sigma_s \omega_{cs}^2)} \quad (8)$$

$$D = -i \sum_s \frac{\omega_{cs}}{\omega} \frac{\omega_{ps}^2}{(\omega^2 - \sigma_s \omega_{cs}^2)} \quad (9)$$

$$P = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2} \quad (10)$$

With $\omega_{ps}^2 = \frac{4\pi n_s q_s{}^2}{m_s}$ a plasma frequency and $\omega_{cs} = \frac{q_s B_0}{m_s c}$ cyclotron frequency of species s ($s = electron, ion$) and $\sigma_s = qs/|qs|$ is the sign of the charge of species s.

By introducing the refractive index $\vec{n} = \vec{k}c/\omega$. The equation (5) is written as

$$\begin{pmatrix} S - n^2cos^2\theta & -iD & n^2cos^2\theta \\ iD & S - n^2 & 0 \\ n^2cos^2\theta sin^2\theta & O & P - n^2sin^2\theta \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0 \quad (11)$$

The solvability condition of this system implies that its determinant is zero, which gives the following dispersion relation [6]:

$$An^4 + Bn^2 + C = 0 \quad (12)$$

$$A = S\,sin^2\theta + P\,cos^2\theta \quad (13)$$

$$B = RL\,sin^2\theta + PS\,(1 + cos^2\theta) \quad (14)$$

$$C = P\,R\,L \quad (15)$$

The solution of this quartic equation given in terms of angle θ by the following dispersion relation:

$$tan^2\theta = -\frac{p(n^2 - R)(n^2 - L)}{(sn^2 - RL)(n^2 - P)} \quad (16)$$

For the special case of wave propagation *parallel* to the magnetic field and $\theta = 0$, the above expression reduces to

$$P = 0,\ n^2 = R = L \quad (17)$$

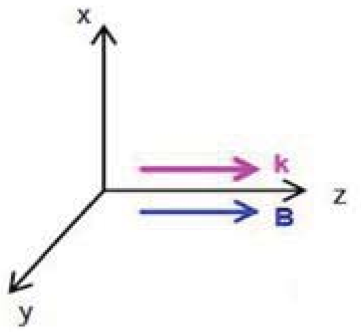


Fig. 1. Parallel propagation to magnetic field $\theta\ = 0$.

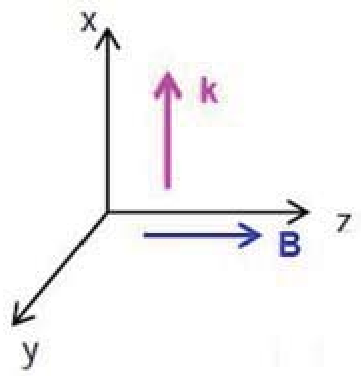


Fig. 2. Perpendicular propagation to magnetic field $\theta\ = \pi/2$.

Likewise, for the special case of propagation *perpendicular* to the field and $\theta\ = \pi/2$, Eq. (16) yields

$$n^2 = \frac{R\,L}{s} = P \tag{18}$$

There is another case of study can be conducted for any θ angle: is the *MHD limit* [5], [3].

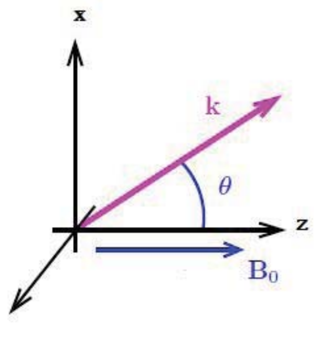


Fig. 3. Propagation to magnetic field for any θ .

IV. ALFVÈN WAVES

Branches of dispersion oblique propagation have a complicated expression because the continuation between θ = π / 2 and θ = 0. In this case the wave propagates with a low frequency approximation checking the magnetohydrodynamic (MHD) $\omega \ll \omega_{ci}, \omega_{pi}$. The elements of dielectric tensor are given by:

$$S = 1 + \frac{\omega_{pi}^2}{\omega_{ci}^2 - \omega^2} + \frac{\omega_{pe}^2}{\omega_{pe}^2 - \omega^2} \approx 1 + \frac{\omega_{pi}^2}{\omega_{ci}^2} = 1 + \frac{c^2}{v_a^2} \tag{19}$$

$$D \approx \frac{i\omega}{\omega_{ci}} \frac{c^2}{v_a^2} \approx 0 \tag{20}$$

$$P \approx 1 - \frac{\omega_{pi}^2 + \omega_{pe}^2}{\omega^2} \approx 1 - \frac{c^2}{v_a^2}\frac{\omega_{ci}\omega_{ce}}{\omega^2} \approx -\frac{\omega_{pe}^2}{\omega^2} \gg 1$$

$$P \to \infty \tag{21}$$

Here, we used the quasi-neutral plasma, which is written $\omega_{pe}^2/\omega_{ce} = -\omega_{pi}^2/\omega_{ci}$

And the system of eigenvalues (11) reduces to

$$\begin{cases} \left(-n^2 cos^2\theta + 1 + \frac{c^2}{v_a^2}\right) \mathrm{E_x} = 0 \\ \left(-n^2 + 1 + \frac{c^2}{v_a^2}\right) \mathrm{E_y} = 0 \\ (\infty) E_z = 0 \end{cases} \tag{21}$$

A. Shear Alfvén wave (Torsional Alfven wave):

The first equation (21) gives the dispersion relation

$$n^2 cos^2\theta = 1 + \frac{c^2}{v_a^2} \tag{22}$$

With $Ex\ \neq\ 0$ and $Ey\ =\ 0$. It is fairly easy to show, from the definitions of the plasma and cyclotron frequencies that $\frac{\omega_{pi}^2}{\omega_{ci}^2} = \frac{c^2}{v_a^2}$. Here, $\rho\ \simeq\ nm_i$ is the plasma mass density, and

$$v_a = \sqrt{\frac{B_0^2}{\mu_0 \rho}} \tag{23}$$

is called the *Alfvén velocity.* Thus, the dispersion relations of the two low-frequency waves can be written

$$\omega \approx k v_a cos\theta \equiv k_{II} v_a \tag{24}$$

With a phase velocity

$$v_\varphi \approx v_a^2 cos^2\theta \tag{25}$$

It is interesting to note that the magnetic perturbation induces torsion of field lines and is therefore called *slow* or *shear* Alfvén wave [7], [8]; see Figure 2.10 (a).

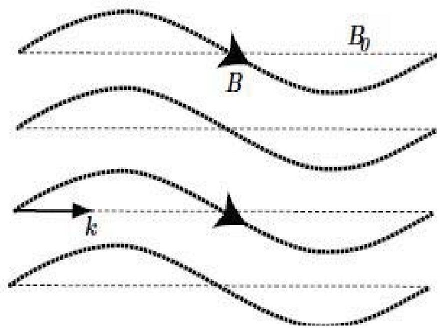


Fig. 4. (a) Magnetic field perturbation associated with a shear-Alfvén wave

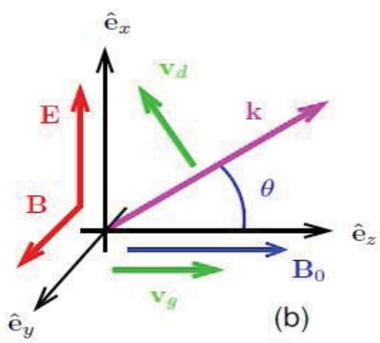


Fig. 4. (b) Polarisation

B. Compressional Alfvèn waves

The second solution of (21) gives the dispersion relation

$$n^2 = 1 + \frac{c^2}{v_a^2} \tag{26}$$

With $Ex = Ez = 0$ and $Ey \neq 0$.
Thus, the dispersion relations of the two low-frequency waves can be written

$$\omega = \frac{kv_a}{\sqrt{1+v_a^2/c^2}} \approx kv_a \tag{27}$$

With a phase velocity

$$v_\varphi \approx \frac{c}{\sqrt{1+c^2/v_a^2}} = v_a \tag{28}$$

Figure 5(a) shows the characteristic distortion of the magnetic field associated with a compressional-Alfvén wave propagating perpendicular to the equilibrium field. Clearly, this wave compresses magnetic field-lines without bending them and this mode is usually called the *fast* or *compressional* Alfven wave also ion magnetosonic wave [7], [8].

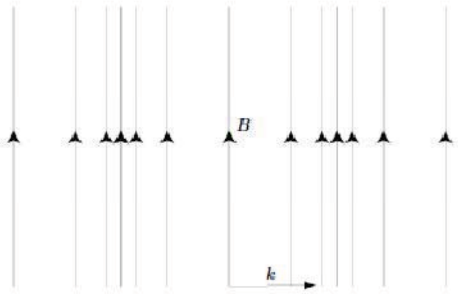


Fig. 5. (a) Magnetic field perturbation associated with a compressional Alfén-wave.

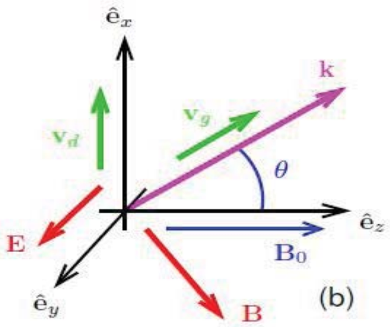
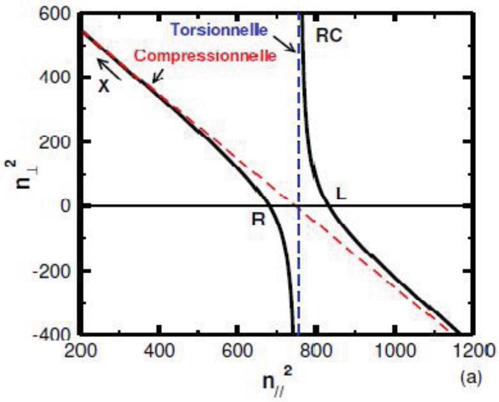


Fig. 5. (b) Polarization

C. *Case of hydrogen plasma*



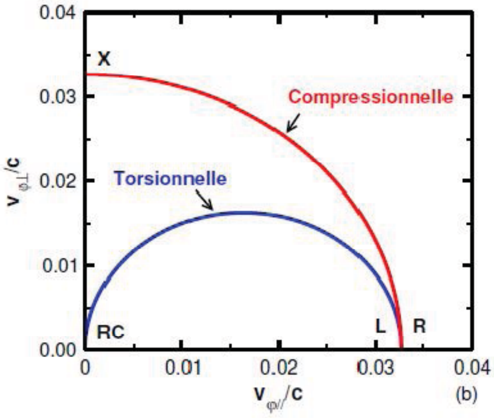


Fig. 6. (a) Hyperbola dispersion (b) Surface velocities of phases in hydrogen plasma with $\omega/\omega_{ci} = 0.1$ and $\omega_{pe}^2/\omega_{ce}{}^2 = 0.4$

Where"R" and "L" refer to right and left whistlers, respectively. "RC" means the resonance cone and "X" the extraordinary mode. To summarize the characteristics of their dispersion relations shows the hyperbola dispersion and the surface phase velocities of the two waves on Figures 6 (a) and (b). We can see that *shear wave* is related to the branch of the whistler L for propagation parallel, and the resonance cone for propagation perpendicular. The compressional wave belongs to the branch R-X. Note that the resonance cone has a vertical asymptote, which is associated with the fact that the dispersion relation of the torsional wave does appear by $n_\perp$, then it sets n_{II}.

To further analyze the propagation of these modes, it is instructive to represent their group velocities where the group velocity is defined by its two components parallel and perpendicular to $\overrightarrow{B_0}$.

$$v_{gII} = \frac{\partial\omega}{\partial k_x} \tag{60}$$

$$v_{g\perp} = \frac{\partial\omega}{\partial k_z} \tag{61}$$

Then we can draw the following table, providing the various expressions of the group velocity for the three modes.

TABLE 1: GROUP VELOCITY FOR THREE MODES.

	v_{gII}	$v_{g\perp}$
Alfvèn mode	v_a	0
Fast mode	$v_+ sin\theta[1 + F_1 sin^2\theta]$	$v_+ sin\theta[1 + F_1 cos^2\theta]$
Slow mode	$v_- cos\theta[1 + F_2 sin^2\theta]$	$v_- cos\theta[1 + F_2 cos^2\theta]$

With

$$F_1 = \frac{v_c^2}{v_+^2}\frac{1}{1-2v_+^2/(v_a^2+v_s^2)} \tag{62}$$

And

$$F_2 = \frac{v_c^2}{v_-^2}\frac{1}{1-2v_-^2/(v_a^2+v_s^2)} \tag{63}$$

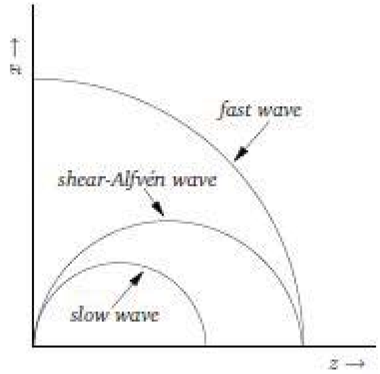


Fig. 7. Phase velocities of the three MHD waves in the x-z plane.

Figure 7 shows the phase velocities of the three MHD waves plotted in the x-z plane for a low-β plasma in which $v_s < v_a$. It can be seen that the slow wave always has a smaller phase velocity than the shear-Alfvén wave, which, in turn, always has a smaller phase velocity than the fast wave.

- Alfvèn velocities for different plasmas are given by the following table:

TABLE 2: ALFVEN VELOCITIES

Quantity	Value	Tok	Co	SWS	EaM	InM
Alfvèn velocity	$V_A=2.18 10^{16} \frac{B}{\sqrt{AZ_n}}$	$6.5 10^6$	$6.5 10^6$	$4.1 10^3$	$6.5 10^6$	

With:

Tok= Tokamaks ($n=10^{20}$ m^{-3}, $T=10^8$ K, B=3T),

C= Corona ($n=10^{16}$ m^{-3}, $T=10^6$ K, B=0.03T),

SW= Solar Wind ($n=10^7$ m^{-3}, $T=10^5$ K, $B=6.10^{-9}$),

EaM= Earth's Magnetosphere ($n=10^{10}$ m^{-3}, $T=10^4$ K, $B=3.10^{-9}T$),

InM= Interstellar Medium ($n=10^6$ m^{-3}, T=100 K, $B=10^{-10}$ T).

III. ROLE OF ALFVÈN WAVES IN PLASMA HEATING

A. TCA Tokamak (1980)

The TCA (acronyme of Tokamak à Chauffage par onde d'Alfvén) refers to the circular section tokamak du CRPP with the main objective is to investigate the possibility of plasma heating by dissipation of Alfvèn waves [Cheethan 1980, TCA Team 1985]. It is characterized by the parameters:

TABLE 3: TOKAMAK PARAMETERS

Parameters	values
Major plasma radius	R=60.5 cm
Minor plasma radius	a=18 cm
Toroïdal magnetic field on axis	B=1.5 Tesla
Plasma current	I_P=170 kA
Safety factor(cylindric)	q(a)=1.9
Ohmic power	P_{oh}=250kW
Total duration of the plasma	t_{pl}=200 ms

(a)

(b)

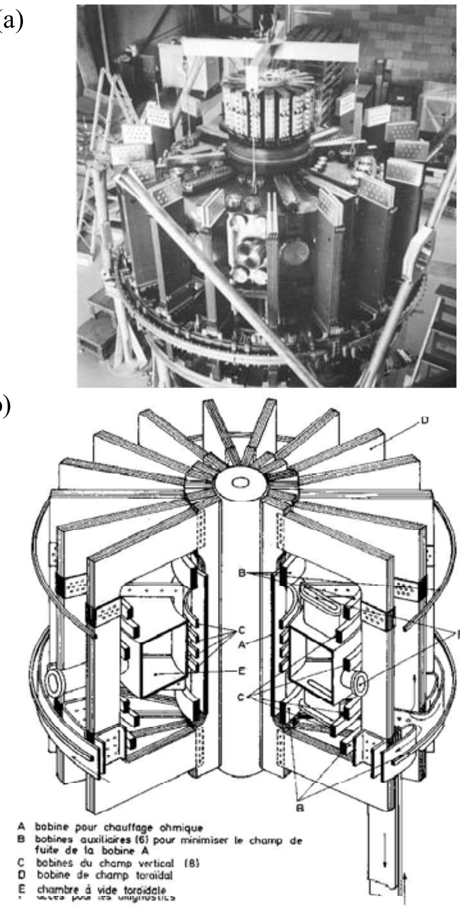


Fig. 8. (a) TCA Tokamak during assembly (b) Cut away diagram of TCA

B. Principle of Alfvèn wave heating

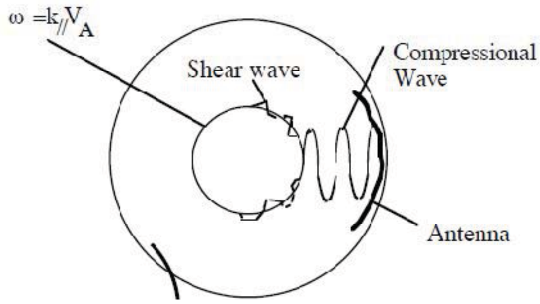


Fig.9. The principle of Alfvèn wave heating. Poloïdal cross-section of the tokamak [9].

In the Alfvén wave domain, we found two types of cold plasma waves that can propagate (see section 4), the shear Alfvén wave (SW) which has dispersion relation is given by (24) and the compressional Alfvén wave (FW) which has dispersion relation is given by (27).

The first of these relations implies that the shear Alfvén wave can propagate only along the field lines.

In an inhomogeneous plasma there is only one surface, close to a magnetic surface, where for a given $N_{//}$ the shear wave dispersion relation Eq.(24) is satisfied. So, the shear Alfvén wave can propagate only on that surface, as shown on Fig.9: it is trapped on that surface.

Therefore, the idea is to launch from the outside the compressional Alfvén wave, which can propagate in all directions and reach the Alfvén resonance. Once the power is coupled to the shear wave, it stays on the magnetic surface and dissipates there. Note that the wavelength of the compressional wave is of the order of 1m. This means that, for 1m wide or narrower antennas, most of the wave spectrum will be evanescent with an evanescence length of the order of the antenna size [10].

From the experimental point of view the most extensive experiments and analysis of Alfvén wave heating have been performed on the TCA tokamak [11], (see figure 8). Although antenna coupling and general wave behavior appeared to be in agreement with the theory, generally speaking little plasma heating was observed while the main effect of the RF was a large density increase, sometimes interpreted as an increase in the particle confinement time. In view of these disappointing results there have been few attempts to apply Alfvén wave heating to large tokamaks and this method is usually not mentioned for the heating of ITER or reactors. However, there has been some renewed interest in this field as the conversion to the kinetic Alfvén wave may induce poloidal shear flows, and possibly generate transport Barriers [11].

V. CONCLUSION

In this paper, we present the study of Alfvén waves which are waves of magnetohydrodynamic origin resulting from coupling between the magnetic field and velocity field. They have the characteristic of transverse magnetic field and propagate with a speed proportional to the external magnetic field. It is a simple solution of the MHD system equations. These waves occur in many astrophysical and geophysical. Its domain of validity is that of large scale with low frequencies like physics of stellar winds and solar physics domains.

There are *three* different types of wave that can propagate through MHD plasma. The first type is termed as the shear-Alfvén wave.

The properties of these waves in warm (*i.e.*, non-zero pressure) plasma are unchanged from those we found earlier in a cold plasma. The two others types correspond to fast magnetosonic and wave the slow magnetosonic wave which are associated with non-zero perturbations in the plasma density and pressure, and also involve plasma motion parallel, as well as perpendicular, to the magnetic field. Their dispersion relations are likely to undergo significant modification in collisionless plasmas. Thus, we can identify the fast wave as the compressional-Alfvén wave modified by a non-zero plasma pressure.

In low-β plasmas the slow wave is a sound wave modified by the presence of the magnetic field.

A unique feature of the "shear" Alfven wave in ideal MHD is the fact that wave energy propagates along the magnetic field, regardless of the angle of the wave front with the magnetic field. This feature leads to several fascinating phenomena.

Heating plasma by resonant absorption of Alfvén waves is a technique that combines low-frequency conventional technology and low cost of installed capacity. The TCA Tokamak (Switzerland) is the largest machine and the most powerful and best equipped in diagnostics which provided the most detailed results on the spectrum and heating by Alfven waves. Its purpose is to study the excitation and absorption Alfvén waves in plasma, showing the usefulness of these waves in the additional heating.

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Auteur : N.G. Sabri

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STUDY OF THE ION CYCLOTRON RESONANCE HEATING IN TOKAMAK PLASMA

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Abstract:

A tokamak is a magnetically confined reactor with high temperature plasma to reach ignition for the generation of thermonuclear power. The plasma of a tokamak cannot be heated to ignition using ohmic heating alone, since joule-heating efficiency decreases with increase in plasma temperature and the maximum value of plasma current is limited by the onset of magneto-hydrodynamic instabilities that terminate the discharge. Auxiliary heating therefore is essential to achieve the goal.

Radio frequency (RF) heating of tokamak plasmas is one of the most successful auxiliary heating schemes at present. Different frequency ranges have been tried in different experiments.

Ion cyclotron resonance frequency (ICRF) range has been very successfully used up to multi-megawatt power levels in tokamaks.

The resonant cyclotron absorption is more efficient with a plasma containing two species of different ions (to avoid the shielding effect). The minority heating method is used. It uses a plasma composed of a mixture of hydrogen ions and deuterium ions. The ratio of the densities of hydrogen and deuterium n_H / n_D is very low. The wave frequency used is hydrogen which is the minority species. The wave is so strongly absorbed in the resonance zone by hydrogen ions. These hydrogen ions will be greatly accelerated; energy will grow and will be transmitted to the rest of the plasma by collisions.

Keys words:

Tokamak, heating, Ion, cyclotron, resonance, absorption