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THE INFLUENCE OF AN ELECTROSTATIC FIELD ON CYCLOTRON RESONANCE BEHAVIOUR OF A PLASMA

by

D.C. Schram, P. Manintveld and E. Oord

Association Euratom-FOM
FOM-Instituut voor Plasma-Fysica
Rijnhuizen, Jutphaas, The Netherlands

Abstract

The theoretically predicted influence of an electrostatic field on the energy gain of electrons at e.c.r. is confirmed experimentally by measuring the loss tangent of the plasma as a function of an applied D.C. voltage. The applicability of this effect as a heating scheme is discussed in general terms.

In a recent publication[1] the influence of an electrostatic field on the energy gain of charged particles at cyclotron resonance has been studied. Here a circularly polarized TEM wave (ω, k) was assumed to propagate along a uniform static magnetic field. In the following $g=e\tilde{E}/m\omega c$, $a=eE_o/m\omega v_p$, $\beta=eB_o/m\omega-1$, are parameters defining the e.m. wave, the e.s. field, and the static magnetic field resp.; $\alpha=n_e e^2/m\varepsilon_o\omega^2=\omega_p^2/\omega^2$, is a parameter for the electron number density, n_e. Close to the resonance even a weak external effect, here an e.s. field, has a considerable influence on the motion of single electrons, resulting in a change of the characteristics of plasma.

In the absence of an e.s. field, the so-called "undisturbed case", the energy of the particle is a periodic function of time, Fig. 1 curve "0", and an oscillation time t_{os} can be defined. This remains valid if the relativistic mass variation and axial velocity variation due to the Lorentz force are taken into account.[3]

In the presence of an e.s. field two regimes can be distinguished, depending on the time scale on which the e.s.field causes a certain change of the resonance function, $r(t)=(\omega-kv_z-\Omega(t))/\omega^{2)}$:

- "strong external effect", the particle is pulled out of resonance within the first oscillation period. A stepwise energy increase is found (curves "1.03", "2" of Fig. 1).
- "weak external effect", the particle remains close to resonance: a continuous increase in energy is added to the undisturbed oscillatory behaviour (Fig. 1, curves ".1", ".5").

At the transition, $a=a_{synchr.}$, defined as the synchronous case, a continuous increase in energy occurs (Fig. 1, curve "1").

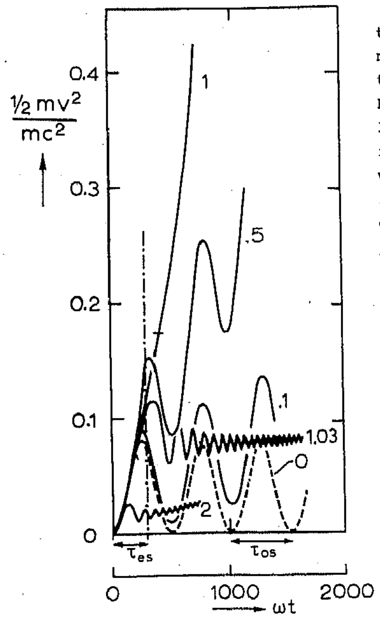

Fig. 1.

Numerically calculated gain of kinetic energy as a function of time; $c^2/v_p^2=0.75$, $g=2.10^{-3}$, $v(t=0)=0, \beta=0$, $a_{synchr.}=1.2\times10^{-4}$. The quantity $a/a_{synchr.}$ is curve parameter.

The reactive and resistive behaviour of the plasma has been studied for the "undisturbed case" in Ref. 3. Using the same calibration for the electric field strength of the e.m. wave as in Ref.3, we find for $\beta=0$ (at cyclotron resonance), a=0(no e.s.field):

$$\left.\frac{1-\varepsilon}{\alpha}\right|_{\beta=0,a=0} \cong 900\ P_{in}^{-1/3}$$

where P_{in} is the incident power of the e.m. wave in Watts. If an e.s.field is applied a part of the electrons is accelerated and a part is decelerated. This leads to resonance functions of opposite sign and, consequently, to dielectric currents of opposite phase. For high values of the e.s. field parameter a, the permittivity, ε, tends to the vacuum value 1.

The loss tangent of the plasma can be calculated if the time of escape of the particles is known. Experimentally[3)]

$$t_{es} \approx 1/2\ t_{os}\Big|_{\beta=0,a=0} \quad \text{yielding} \quad \left.\frac{tg\delta}{\alpha}\right|_{\beta=0,a=0} \cong 620\ P_{in}^{-1/3}\ .$$

Evidently, the loss tangent will show a weak maximum for $a=a_{synchr.}$. For values of $a>a_{synchr.}$ the step in energy decreases with increasing a. Consequently, if the escape time is assumed to be independent of a, the loss tangent decreases.

The experimental facility shown in Figs. 9, 10 of Ref. 3 has been used for the measurements. Two electrodes were mounted on the axis and a negative D.C. voltage was applied. The magnetic field strength of the static magnetic field was chosen such that the cyclotron frequency was equal to the applied frequency (β=0). The loss tangent, the permittivity, and the density of the plasma were measured as functions of the applied D.C. voltage for several values of P_{in}. The result for P_{in}=20W are plotted in Fig. 2 (normalized to the density); the loss tangent shows a maximum at V=2.2.Volt, taken to be $V_{synchr.}$. Values of $V_{synchr.}$ for various values of P_{in} are plotted in Fig. 3.

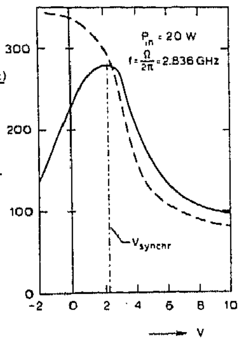

Fig. 2.

Measured loss tangent and dielectric constant as functions of the applied D.C.voltage. $V_{synchr.}$ is the value of V where $tg\delta/\alpha$ is max.

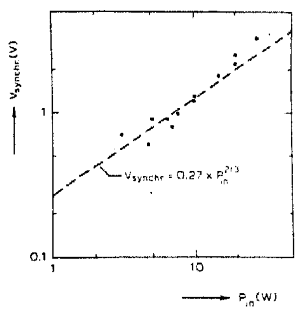

Fig. 3.

$V_{synchr.}$ as a function of P_{in}. The dashed line is the theoretically predicted curve for a Debye length $\lambda_D \sim 1$ cm.

As predicted in Ref. 1 we find $V_{synchr.} \propto P_{in}^{2/3}$. Taking the field calibration of Ref. 3, we find theoretically $a_{synchr.} = .92\times10^{-6}\times P_{in}^{2/3}$. The e.s. field is assumed to be constant over a shielding length λ_D of 1 cm, which corresponds to the measured $n_e \approx 3\times10^{17}$/cc and the estimated parallel electron energy of 50 eV. The experimental result, $V_{synchr.} = .27\times P_{in}^{2/3}$, is in agreement with theoretical predictions.

Discussion

The mechanisms discussed here may, in more general terms, be applied to heat plasmas. A discussion of both cases, weak and strong external effects, may be of interest.

If the external effect is weak, the energy grows without any limitation but time. However, even if the density is small the plasma can become extremely reactive, while for higher densities cyclotron absorption will damp the wave before large energies are reached. As a heating scheme it is only attractive in very tenuous plasmas of large dimensions, e.g. extra terrestial plasmas.

In a strong e.s. field a quasi-collisional energy gain occurs. The reactive components of the current are relatively low and can be chosen zero by choosing a value of β slightly different from zero. The permittivity of the plasma is close to the vacuum value. This mechanism could be applied as a heating mechanism in which the heating rate can be chosen. It should be remarked that the external field need not be static: e.g. an e.s. field varying slowly with respect to t_{os} leads to repetitive heating. Such electrostatic waves can be introduced into the plasma.Frequency modulation is an attractive alternative as an external mechanism.

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