An experiment on cyclotron resonance heating of ions and electrons in a plasma
- Final Report -

G.Cattanei, A.C. England, G.Siller

IPP 2/81

August 1969

INSTITUT FÜR PLASMAPHYSIK
GARCHING BEI MÜNCHEN

INSTITUT FÜR PLASMAPHYSIK

GARCHING BEI MÜNCHEN

An experiment on cyclotron resonance heating of ions and electrons in a plasma
- Final Report -

G.Cattanei, A.C. England, G.Siller

IPP 2/81 August 1969

Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Institut für Plasmaphysik GmbH und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

IPP 2/81

G. Cattanei
A.C. England +)
G. Siller

An experiment on cyclotron resonance heating of ions and electrons in a plasma

- Final report -

August 1969
(in English)

Abstract

This report describes some results of an experiment in which ions and electrons were to be heated independently at the respective cyclotron resonance frequency. As the experiment was shut down before systematic measurements could be made, the behaviour of the plasma could only be qualitatively determined.

+) On leave from Oak Ridge National Laboratory, Oak Ridge, Tenn./USA

Introduction

One of the most successful methods of heating a plasma is by conversion of the electromagnetic energy of a wave into thermal energy of the plasma. If the plasma is immersed in a static magnetic field, a wave propagating close to the cyclotron frequency of one type of plasma particles will convert its energy into random motion of those particles by the process of cyclotron damping.

The main purpose of our experiment, "Selene", was to create a plasma in which ions and electrons could be heated independently at the respective cyclotron frequencies. This experiment arose from previous theoretical work for a larger project "Helios" [1, 2], which was never realized. Some parts of the Helios project such as the r.f. transmitter which were already available were utilized.

We started the experiment with a simple magnetic mirror geometry. It was intended to use more complicated magnetic field configurations such as minimum-B only if some evidence could be obtained that the lifetime of the plasma was limited by macroscopic instabilities.

The microwave power for electron cyclotron resonance heating (E.C.R.H.) was fed into the device by horns. For ion cyclotron resonance heating (I.C.R.H.) the method proposed by Stix [3] was used.

The experiment had to be abandoned before conclusive measurements could be made. The information reported here is therefore only preliminary and qualitative.

Some of the most important results obtained elsewhere by I.C.R.H. are summarized in the following paragraphs and compared with our experiment. A survey article of experiments on ion cyclotron resonance in plasma up to 1963 has been written by Hooke et.al. [4] and a complete bibliography of the work done in this field can be found in a recent paper of Christiansen [5].

At the Princeton Plasma Physics Laboratory, Hooke et.al. [6] heated the ions of a 10-liter plasma in the magnetic mirror device B-66 to a temperature T_i = 200...300 eV. In a small volume near the resonant region the ion temperature could reach 1 keV.

In the B-66 experiment only a low preionization of the plasma was used and the plasma density was increased to $n_e \approx 3\times10^{13}\,cm^{-3}$ by the r.f. power itself. The main energy loss rate with a decay time τ = 30-50 μsec, was cooling of the ions by collision with cold electrons, $T_e \lesssim 12$ eV, which in turn lost their energy in inelastic collisions with impurities or in the sheath at the end of the mirror device.

In our experiment the plasma produced by microwave power was expected to have a larger degree of ionization, higher electron temperature, and less impurities. The energy loss rate should therefore be greatly decreased with respect to the limits found by Hooke et.al.
In the C-stellarator [7] a small fraction, (local mirror V = 5 liters) of the whole plasma volume, V = 300 liters, could be heated by I.C.R.H. up to an ion temperature T_i = 3 keV. The plasma was produced by ohmic heating and the electron temperature reached T_e = 100 eV. The upper limit of the confinement time of the hot ions, τ = 1 msec, could be accounted for by energy losses due to charge exchange with neutral hydrogen coming from the wall. The limitation on the ion temperature, $T_i \lesssim 3$ keV, was attributed either to a decrease in the rate of r.f. energy absorption due to the anisotropic velocity distribution, $T_\perp \gg T_\parallel$ produced by I.C.R.H. [8], or to the diffusive nature of resonant cyclotron heating, which causes the hotter particles to be scattered out of the mirror [9].In our experiment the neutral gas pressure should be greatly reduced in comparison to the C-stellarator, where a large neutral gas flux is produced by recycling of the particles lost to the wall by the main body of the plasma. The energy losses due to charge exchange should therefore be much less than in the C-stellarator.

The mirror ratio in our experiment was larger than in the C-stellarator, and higher values of the ion temperature should have been possible if scattering of the hot particles out of the mirror limited the maximum temperature which could be attained. We must note, however, that interchange instabilities may become much more dangerous in our experiment. Such instabilities may have been stabilized in the C-stellarator by line-tying. The hot-ion plasma in the local mirror was, in fact, connected along the magnetic lines of force to the main body of the stellarator plasma, which in turn was made stable by the shear of the helical windings. In our experiment the cold plasma produced by electron cyclotron heating should also ensure line tying to the metallic end plates. This effect, however, is severely reduced when a high degree of ionization and high plasma temperature is achieved by ion cyclotron heating in the magnetic mirror.

Experimental set-up

A block diagram of the experimental set-up is shown in fig. 1. The central part of the vacuum vessel consists of a glass cylinder of 1 m length and 15 cm diameter. The whole apparatus has a length of 2.6 m. It was evacuated by one 500-liter pump at each end, which ensured a base pressure of 10^{-7} torr. The magnetic field was a simple magnetic mirror with a central region where the magnetic field was kept constant over a length of 50 cm. The magnetic field decreased at both sides of the constant region to a minimum (magnetic beach) and increased again towards the throat of the mirror. The three regions, i.e. constant magnetic field, beaches, and mirror, could be controlled independently so that it was possible to change the mirror ratio or the depth of the beach while leaving the magnetic field in the middle constant. The maximum mirror ratio was R = 2 with a magnetic field in the constant region of 4 kG.

The plasma was created by the microwave power. Two klystrons were available: 10.6 GHz, 2 kW, c.w. and 15.7 GHz, 2 kW, 1-20 msec pulsed. The microwave power was fed at both ends of the device, near the beach region. The E.C.R. region for the 10.6 GHz power was in the vicinity of the minimum magnetic field, while the 15.7 GHz power was in resonance near the maximum of the mirror. The r.f. generator could supply 1 MW of power at a frequency of 6 MHz for a duration of 10 msec. The r.f.power was coupled to the plasma in the constant magnetic field region by a Faraday shielded Stix coil. In the original transmitter the Stix coil formed part of the oscillating circuit. The Stix coil consisted of 5 single turns in parallel. The turns were spaced 10 cm apart and the current in adjacent turns was 180° out of phase. This corresponded to a fundamental wave length, $\lambda_o = 20$ cm.

Such a coil is theoretically predicted [3, 10] to have a relatively low Q $[Q = \frac{\text{power stored in the coil}}{\text{power absorbed by the plasma}}]$. For this reason one would expect to be able to couple a sufficient amount of power to the plasma in spite of the lack of flexibility of the matching system.

Diagnostics

The plasma density was measured by an 8 mm microwave interferometer in the constant magnetic field region. Three diamagnetic probes were used. Two of them, 50 turns and 10 turns, respectively, were placed at the end of the glass section 15 cm from the minimum of the beach, while the third, a 50-turn diamagnetic probe, was placed around the metallic vessel at the magnetic beach. Two magnetic probes could be moved from the ends to detect the longitudinal and radial r.f. magnetic fields. A Langmuir probe was inserted in the region of the magnetic beach.

Directional couplers were used to measure the incident and the reflected r.f. power.

Experimental results

When the experiment was initiated, only the 10.6 GHz microwave power was available. For typical gas pressure $p = 5 \times 10^{-5}$ torr a plasma density $n = 6 \times 10^{10}$ cm^{-3} and an electron temperature $T_e = 30$ eV were obtained. The decay time of the plasma was $\tau = 100$ µsec. By increasing the neutral gas pressure the plasma density increased slightly but remained $n \lesssim 10^{11}$ cm^{-3}.

The maximum degree of ionization was about 20 %. With the density assumed to be constant over the 15 liter plasma volume, a microwave efficiency of 6 % was estimated. Applying r.f. power did not increase the plasma density, and no significant amount of r.f. power could be coupled to the plasma. The resistive plasma loading of the Stix coil was considerably less than theoretically predicted, and this coused a complete mismatch of the r.f. power. With the avialable r.f. system it was, in fact, not possible to match the r.f. power to the plasma for such high Q values of the Stix coil owing to the frequency change caused during the pulse by the plasma loading the oscillator. As already mentioned, we used a self-excited r.f. transmitter inherited from the Helios project. The problem of the unexpectedly low resistive plasma loading will be treated in the next section, where the influence of the finite plasma temperature on the coupling of cyclotron waves will be considered.

Theoretical considerations

The Q of the Stix coil was evaluated for "coupling resonance" i.e. when the axial wavelength λ_o of the coil equals the axial wavelength λ_z of a natural mode of free propagation for a cyclotron wave in a bounded plasma. For a plasma cylinder surrounded by vacuum the boundary conditions require that:

$$\frac{k_r J_0(k_r \rho)}{J_1(k_r \rho)} = - \frac{k_z K_0(k_z \rho)}{K_1(k_z \rho)} \tag{1}$$

with Bessel function in the notation of G.N. Watson. The quantities k_r and k_z are related by the dispersion relation, which for a cold plasma with the magnetic field B in the z direction and ω sufficiently close to ω_{ci} is:

$$k_r^2 = -k_z^2 \frac{k_z^2 c^2 - \omega_{pi}^2 \dfrac{\omega}{\omega_{ci} - \omega}}{k_z^2 c^2 - \dfrac{\omega_{pi}^2}{2} \dfrac{\omega}{\omega_{ci} - \omega}} \tag{2}$$

k_r and k_z are the radial and axial wave numbers respectively, ρ is the plasma radius, $\omega_{pi} = \left(\frac{4\pi n_i e^2}{m_i}\right)^{1/2}$ is the ion plasma frequency, and ω_{ci} is the ion cyclotron frequency. For "coupling resonance", $\lambda_z = \lambda_0$, eq. (1) has solutions only for k real and from eq. (2) one obtains the condition

$$k_z^2 c^2 < \omega_{pi}^2 \frac{\omega}{\omega_{ci} - \omega} < 2 k_z^2 c^2 \tag{3}$$

For low plasma density ω must be very close to ω_{ci} in order to satisfy eq. (3); therefore, under the conditions here, it is no longer possible to neglect the thermal motion of the plasma particles. If a Maxwellian velocity distribution is assumed the first finite temperature correction to the cold plasma relation (2) is:

$$k_r^2 = -k_z^2 \frac{k_z^2 c^2 - \omega_{pi}^2 \zeta_0^{(i)} Z_1^{(i)}}{k_z^2 c^2 - \dfrac{\omega_{pi}^2}{2} \zeta_0^{(i)} Z_1^{(i)}} \tag{4}$$

where $\zeta_n^{(i)} = \frac{\omega - n\omega_{ci}}{k_z} \left(\frac{m_i}{2\kappa T_i} \right)^{1/2}$

and $Z_n^{(i)} = \left[i\sqrt{\pi} \frac{k_z}{|k_z|} - 2 \int_0^{\zeta_n^{(i)}} \exp(t^2)\, dt \right] \exp\left[-(\zeta_n^{(i)})^2 \right]$

is the plasma dispersion function, $\varkappa$ is the Boltzmann constant, and m_i, T_i are the ion mass and temperature respectively. Equation (4) is valid for $|\xi_0^{(i)}| \gg 1$ and $(\omega_{pi}/\omega)^2 \gg 1$ both conditions being satisfied for $\lambda_z \approx 20$ cm and a wave frequency $f = 6 \times 10^6$ sec^{-1} if $T_i \ll 7.5 \times 10^3$ eV and $n_i \gg 10^9$ cm^{-3}. If $|\xi_1^{(i)}| \gg 1$, then $Z_1^{(i)} \simeq \frac{1}{\xi_1^{(i)}}$ and eq. (4) reduces to the cold plasma dispersion relation (2). Thus for a finite temperature plasma condition (3) can be rewritten:

$$k_z^2 c^2 < \omega_{pi}^2 \xi_0^{(i)} \, \mathrm{Re}\left[Z_1^{(i)} \right] < 2 k_\perp^2 c^2 \tag{5}$$

As the real part of $Z_1^{(i)}$ is limited, $|\mathrm{Re}(Z_1^{(i)})| \lesssim 1$, there is a minimum density for which coupling resonance can occur. For our parameters, $\lambda_o = 20$ cm and $f = 6 \times 10^6$ sec^{-1}, we obtain:

$$n > 7.5 \times 10^{11} \sqrt{\Theta_i} \ \mathrm{cm}^{-3}$$

where Θ_i is the ion temperature in eV.

This condition cannot be satisfied by the densities obtained with the microwave power ($n \lesssim 10^{11}$ cm^{-3}) even for moderately low ion temperatures ($\Theta_i \gtrsim 1$ eV). Plasma densities larger by one order of magnitude or more would be necessary.

Modified set-up

As already pointed out, the plasma density was not increased by the r.f. power. This fact, however, is not in disagreement with the results obtained in the B-66 experiment. The Stix coil used by Hooke et. al. had no Faraday shield and the density was increased by the longitudinal electric field, which is very effective in accelerating electrons along the magnetic lines of forces.

About 80 % of the r.f. power was lost in this way (mode x) [11] and large amounts of impurities were produced by electrons striking the walls.
In our experiment we wanted to maintain the characteristics of a hot electron E.C.R. plasma. Therefore, we tried to couple r.f. power at low plasma densities and not to increase the density much beyond that obtained by the microwave power. Rapid cooling of the ions by cold electrons as in B-66 experiment should thereby be avoided.
From condition (5) it is clear that the lowest plasma density at which coupling resonance can still occur is proportional to $(1/\lambda_o)^3$. It should therefore be possible to couple ion cyclotron waves to a low density plasma simply by increasing the axial wave length λ_o of the Stix coil. A limit for λ_o is imposed, however, by the length of the constant magnetic field region. Moreover, the Q of the Stix coil is theoretically expected to increase very rapidly if $\lambda_o \gg \varrho$, ϱ being the plasma radius. The best compromise in our case was a Stix coil consisting of three double turns spaced 20 cm apart, which corresponds to a fundamental wave length $\lambda_o = 40$ cm. Such a coil is expected to have a much larger Q than the original one. Therefore, in order to match r.f. power to the plasma, the whole r.f. transmitter and matching system had to be redesigned [12]. The new Stix coil has a broad Fourier spectrum of wave lengths, and the condition for coupling resonance should not be too sensitive to the plasma density. Thus, although the lowest plasma density required for coupling resonance is still above the plasma density obtained by microwaves, there will be for a fixed magnetic field some wave length in the long wave length tail of the Fourier spectrum for which coupling resonance occurs. If r.f. power is coupled to the plasma and the plasma density increases, the condition for coupling resonance is shifted towards shorter wave lengths without changing the Q of the coil too much. With the new matching system the voltage at the coil can reach very high values so that particular care was necessary to prevent arcing.

Experimental results

With the new coil and transmitter we observed a different behaviour of the plasma in different neutral gas pressure ranges. For high neutral gas pressure $p \gtrsim 5 \times 10^{-4}$ torr, a sufficient amount of r.f. power (a few kilowatts) could be coupled to the plasma. The plasma density increased by a factor two or more, and at the same time the reflected r.f. power decreased as expected if ion cyclotron waves are coupled to the plasma. A significant diamagnetic signal indicated effective heating of the plasma (several hundred eV).

The decay time of the plasma, however, did not increase as expected if the plasma losses were due to collisions between charged particles. The decay time of the diamagnetic signal ($\tau < 20\ \mu$sec) remained shorter than that of the density ($\tau < 100\ \mu$sec). The ratio of ions to neutral atoms was, however, less than 1 % and the high loss rate can therefore be ascribed to rapid cooling of the "hot" ions due to charge exchange and subsequent loss of the cold plasma from the mirror. The degree of ionisation could not be increased in this neutral gas pressure range because of the small amount of microwave power and the necessity of using an arrangement (glass section under the Stix coil) allowing microwave losses to the room. No large amplitude oscillations or any evidence of instabilities could be observed in this neutral gas pressure range.

At lower neutral gas pressure only a limited amount of r.f. power could be coupled to the plasma. By increasing the r.f. power above a few kwatts large amplitude oscillations in the plasma density $[\nu = 10 \div 100$ kHz, $\Delta n/n \gtrsim 50\ \%]$ and in the diamagnetic signal were observed. The onset of the oscillations was very sensitive to the r.f. power and to the neutral gas pressure. No satisfactory reproducibility could be achieved in this pressure range.

For even lower neutral gas pressure ($p \lesssim 5 \times 10^{-5}$ torr) at the start of the r.f. pulse, the plasma density dropped below the sensitivity of the microwave interferometer (n = a few 10^9 cm^{-3}) in a few μsec. For fixed r.f. power, neutral gas pressure, and plasma density, this effect depended on the mirror ratio and not on the depth of the beach, as if the plasma was accelerated out of the mirror by the r.f. electric field. The microwave power, when operated continuously, again increased the plasma density after the end of the r.f. pulse; however, large amplitude oscillations persisted for a few hundred μsec.

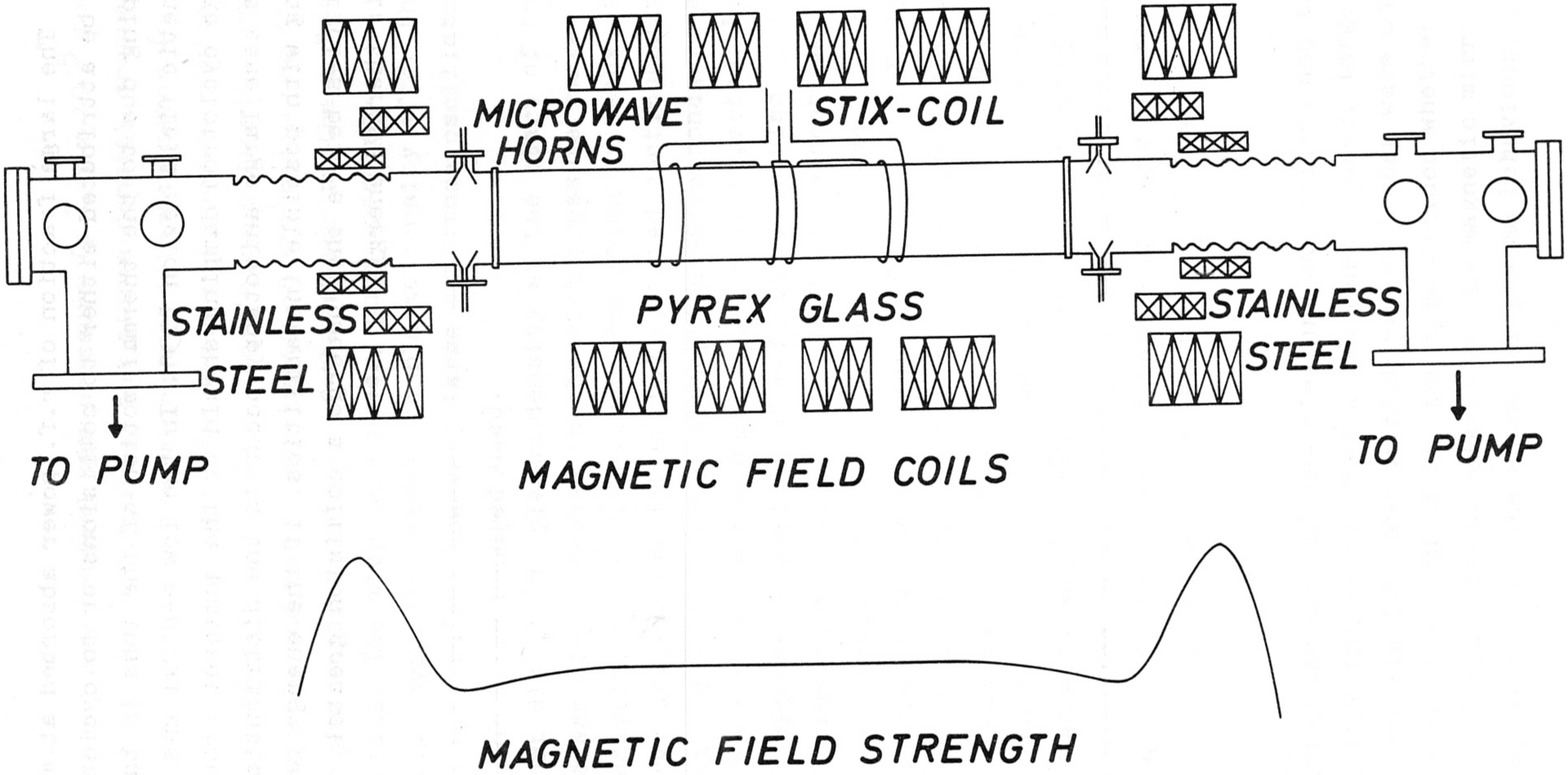
A short dip in the plasma density at the start of the r.f. pulse was also observed in the high pressure range.

An analysis of the r.f. power absorption by means of a low energy transmitter (30 watts) operated continuously showed that the maximum power absorption corresponds to a magnetic field strength for which $\omega_{ci} > \omega$ as expected. However, a considerable fraction of r.f. power is also absorbed by the plasma for $\omega > \omega_{ci}$, and this cannot be explained by coupling of cyclotron waves. No wave propagation should in fact be possible for $\omega > \omega_{ci}$. In the meantime the 17.6 GHz microwave power became available. Its efficiency, however, was very poor, and the plasma density was increased only by a small amount. The E.C.R. region for this frequency was too far from the region where the microwave were fed in so that most of the power could escape from the device (a low Q cavity) before reaching the resonant region. At this stage the experiment was shut down.

Final remarks

Whenever the neutral gas pressure was reduced and the collision time increased above a few tens of μsec, large amplitude oscillations and/or high plasma losses were observed. With the available results it cannot be decided whether or not macroscopic instabilities related to the magnetic mirror are really responsible for the anomalous plasma behaviour.

The large fraction of r.f. power absorbed at $\omega > \omega_{ci}$ can be attributed either to collisions or to cyclotron damping due to the thermal motion of the ions in the constant magnetic field region [13]. In the low neutral gas pressure range cyclotron damping should be the dominant process. In this case large anisotropy occur in the distribution function, along with possible instabilities, if the energy gained by the particles before they undergo a collision greately exceed their thermal energy.



BLOCK DIAGRAM OF THE EXPERIMENTAL SETUP

/1/ F. Boeschoten, G. Cattanei, G. Siller,
EURATOM Symposium on Plasma Physics, Varenna/ Italy 1964

/2/ F. Boeschoten,
Institut für Plasmaphysik, Report IPP 2/44 (1965)

/3/ T.H. Stix,
The Theory of Plasma Waves, McGraw-Hill, New York (1962)

/4/ W.M. Hooke, M.A. Rothman,
Nucl. Fusion 4, 33 (1964)

/5/ M. Kristiansen,
The University of Texas, Ph.D. Thesis (1967)

/6/ W.M. Hooke, M.A. Rothman, J. Sinnis, J. Adam,
Phys. Fluids 8, 1146 (1965)

/7/ H. Yamato, A. Iiyoshi, M.A. Rothman, R.M. Sinclair,S.Yoshikawa
Phys. Fluids 10, 756 (1967)

/8/ A. Iiyoshi, H. Yamato, S. Yoshikawa, Phys. Fluids 10,
749 (1967)

/9/ A.F. Kuckes,
Colloque International sur les Interactions entre les
Champs Oscillants et les Plasmas, (Saclay 1968), Vol. I,
p. 119

/10/ G. Cattanei,
Institut für Plasmaphysik, Report IPP 2/57 (1967)

/11/ S. Yoshikawa, R.M. Sinclair, M.A. Rothman,
Plasma Physics and Controlled Nuclear Fusion Research
(Culham 1966), Vol. 2 , p. 925

/12/ G. Siller,
Institut für Plasmaphysik, Technische Notiz (1967)

/13/ M.P. Vasil'ev, L.I. Grigor'eva, V.V. Dolgopolos, B.I. Smerdov,
K.N. Stepanov, V.V. Chechkin,
Soviet Phys. 9, 755 (1964)