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ELECTRON HEATING IN A PLASMA AT THE CYCLOTRON FREQUENCY IN AN INHOMOGENEOUS MAGNETIC FIELD

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Results on experiments concerned with electron cyclotron heating of a plasma in the L-1 stellarator are reported. The absorption conditions, the decay length for the microwave energy, and the plasma lifetime have been investigated as functions of the magnetic field and the applied microwave energy. It is shown that the plasma lifetime is inversely proportional to the absorbed microwave energy.

1. INTRODUCTION

THE presently available published work on electron-cyclotron absorption of electromagnetic waves in a magnetoactive plasma refers to cases in which the experiments were carried out in a uniform magnetic field or in a mirror field.[1-3] It has been shown in this work that an effective absorption of the wave energy by the plasma occurs under resonance conditions.

It is of interest to investigate cyclotron absorption in a highly inhomogeneous magnetic field, for example, a field such as that in a stellarator. An example of the possible value of investigations of this kind would be the application of this effect for the investigation of plasma confinement in a stellarator at various electron temperatures.

In the present work we have investigated the possibility of electron heating in a plasma confined by a stellarator field. These experiments were carried out in the L-1 stellarator.[4] Experiments on confinement of a low-pressure plasma produced by the injection of plasmoids have shown[5] the nonclassical nature of plasma diffusion in the stellarator. The diffusion coefficient is found to be inversely proportional to the strength of the magnetic field H. On the other hand, the diffusion is not described quantitatively by the well-known Bohm formula (the diffusion is slower); furthermore the diffusion coefficient is found to be sensitive to the value of the rotational transform. The temperature of the electrons in the injected plasma in these experiments is several eV and can not be varied in a controlled way. The effect of absorption of microwave power at the electron-cyclotron frequency might be used as a possible means for heating the plasma electrons.

2. EXPERIMENTAL CONDITIONS

The L-1 stellarator[4] in which these experiments were carried out is a toroidal magnetic system with an $l = 2$ helical field. The vacuum chamber is a metal torus with major radius R = 60 cm and minor radius r = 5 cm. The ratio of the amplitude of the fundamental of the helical field $H_\perp$ to the longitudinal field H_0 in these experiments is $\epsilon = H_\perp/H_0 = 0.33$. The mean rotational transform $i = \pi$ and the value of the mean dimensionless shear (the gradient of the rotational transform of the lines of force) $\theta = r\Delta i/2\pi R \sim 10^{-2}$ where Δi is the difference between the rotational transform at the center of the chamber and at the extreme magnetic surface.

In this work we have used a pulse-modulated microwave source operating in a single-pulse mode whose length can be varied between 2 and 1000 μsec. The wavelength is approximately 4 cm and the power in the pulse can be varied from 100 to 10,000 W. The microwave energy is fed to the chamber by a waveguide which enters one of the tubulations through a ceramic vacuum transition.

A schematic diagram of the vacuum chamber and the location of the various diagnostic devices is shown in Fig. 1. In the present experiments measurements were made of quantities proportional to E^2 by means of the detectors 4 located along the vacuum chamber at various distances ($z_1 = 27$ cm, $z_2 = 40$ cm and $z_3 = 94$ cm) from the point at which the microwave energy is introduced; the incident and reflected power are detected by means of the directional couplers 5 and 6. The measurements of the plasma density as a function of time are carried out by means of microwave elements 9 at a wavelength of 8 mm.[6] Single Langmuir probes 8 are also used.

In the absence of plasma the vacuum chamber represents a resonator. The quality factor of this resonator, determined by measurements of the field amplitude in the resonator as a function of frequency, is found to be $Q \approx 700$. From the conditions for excitation, i.e., the electric field **E** perpendicular to the principal plane of the torus, it follows that TE modes are excited in the resonator. The transverse and axial longitudinal dimensions of the resonator are much larger than the wavelength so that the resonator is excited in higher modes.

In many experiments on investigation of electron-cyclotron resonance in a plasma the microwave energy was also used to ionize the neutral gas in order to produce the plasma in addition to providing the plasma heating. In the present experiment the cyclotron absorption of the power occurs in a plasma which is produced beforehand by external injection. The injection is realized in a quasistationary field. After approximately 100 μsec a quasistationary density distribution is established in the chamber and is maintained during the entire decay time of the plasma. The microwave energy is not switched on until at least 200 μsec after injection. The plasma density at the time the microwave pulse is switched on is less than 10^{10} cm^{-3}. Thus, in these experiments the condition $\omega_{He} \gg \omega_{Le}$ is always satisfied where ω_{Le} is the plasma frequency and ω_{He} is the electron-cyclotron frequency.

The magnetic field in the vacuum chamber of a stellarator is highly inhomogeneous. The absolute value of the magnetic field is a function of the radius r and the azimuthal angle φ and depends on the helical field as well as the toroidal geometry of the system. In Fig. 2a and Fig. 2b we show magnetic isobars (lines $|\mathbf{H}| = \text{const}$) for two cross-sections of the L-1 stellarator for the case $\epsilon = 0.33$. The numbers near the curves denote the quantity H^2/H_0^2 where H_0 is the strength of the magnetic field at the axis of the torus. The pattern in Fig. 2a

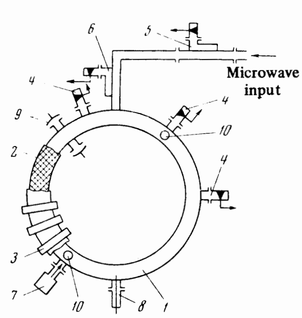

FIG. 1. Diagram of the L-1 stellarator and location of the various elements: 1 – stellarator vacuum chamber, 2 – helical winding, 3 – longitudinal field coil, 4 – pickup unit for measuring the level of the microwave field, 5, 6 – directional couplers, 7 – plasma injector, 8 – Langmuir probe, 9 – microwave diagnostics, 10 – pickup unit for pulsed measurements of the pressure inside the vacuum chamber.

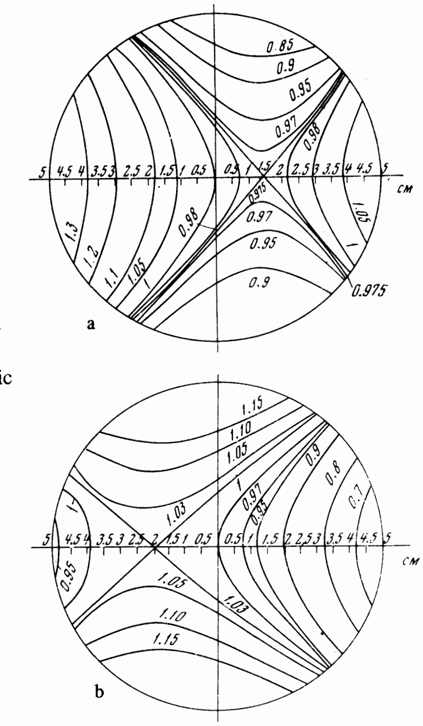

FIG. 2. Magnetic isobars for the L-1 stellarator for $\epsilon = 0.33$. The major axis of the elliptic magnetic surface is oriented as follows: a) vertical, b) horizontal.

corresponds to the case in which the major axis of the elliptical magnetic surface is oriented vertically; in Fig. 2b this axis is oriented horizontally. The distance between these two cross-sections corresponds to ¼ of the pitch of the helical winding (13.5 cm). A detailed discussion of the pattern of magnetic isobars is given below. At this point we merely indicate that the inhomogeneity in the strength of the magnetic field in the region bounded by the magnetic surfaces can reach 20%. The absolute magnitude of the magnetic field $|\mathbf{H}|$ under these conditions varies from $0.83\, H_0$ to $1.07\, H_0$.

3. RESONANCE ABSORPTION OF MICROWAVE ENERGY IN A STELLARATOR FIELD

An investigation was made of the absorption of microwave energy as a function of the strength of the magnetic field.[1)] At magnetic field far from resonance the absorption of microwave energy is small and the stellarator chamber is essentially a resonator, as it is in the case in which there is no plasma. As the plasma density decays in the chamber[2)] there occurs a detuning of the resonance from one mode to another. This detuning[3)] is recorded by the detectors 4 (Fig. 1). As the magnetic field approaches the resonance value the pattern is changed considerably. The electromagnetic wave starts to exhibit absorption and the chamber is no longer a resonator.

In Fig. 3 we show the ratio of the power in the chamber P_{ch} to the incident power P_0 as a function of the

[1)] The magnetic field for which electron-cyclotron resonance occurs in the present work is $H_{res} \approx 2.5$ kOe.

[2)] For a field $H \sim 2.5$ kOe and $\epsilon = 0.33$ the plasma lifetime is approximately 500 μsec.

[3)] Ten percent of the power is reflected and this is due to the lack of an ideal match between the waveguide and the chamber.

magnetic field at the axis for two distances z = 27 cm (curve 1) and z = 94 cm (curve 2) from the point at which the microwave power is introduced. It will be evident that the dependence of P_{ch}/P_0 on H exhibits a resonance nature and that the width of the resonance is determined by the inhomogeneity in the magnetic field over the cross section of the vacuum chamber. The flat nature of the curve is evidently associated with the displacement over the cross section of the chamber of the region in which the exact resonance condition $H = H_{res} = mc\omega/e$ is satisfied, where ω is the microwave frequency. The asymmetry of the curve with respect to the value H_{0res}, for which the resonance condition is satisfied at the axis of the torus, is in good agreement with the calculations given above for the absolute value of the magnetic field inside the stellarator chamber ($0.83\ H_0 \leq |\mathbf{H}| \leq 1.07\ H_0$). The resonance curve should be displaced to the region of higher magnetic fields.

As is evident from curve 2, the wave is essentially completely absorbed at distances less than 90 cm in a wide range of field values. Using the curve we can determine the distribution of microwave energy over the length of the chamber for various magnetic fields and thus determine the effective length at which wave absorption occurs. In Fig. 4 we show the corresponding functional relation obtained for a field $H_0 = 2.4$ kOe, which is close to the resonance value. The absorption curve for the microwave power is essentially exponential within the experimental error of the measurements and the effective attenuation length δ is approximately 15–20 cm. In regions of higher absorption the value of δ is still smaller. These measurements indicate that when the electron-cyclotron resonance condition is satisfied there is an effective absorption of the microwave energy introduced into the stellarator chamber.

The theory of propagation of electromagnetic waves in an infinite uniform plasma indicates that in the region of electron-cyclotron frequency the strong absorption appears only for the extraordinary wave. However, the ordinary wave does not experience severe damping and should propagate over appreciable distances without significant attenuation. A wave with arbitrary polarization can be represented as a superposition of two waves with counter-rotating elliptical polarizations, only one of which will experience strong absorption. From this point of view, in the present case one would expect approximately half of the microwave power to be absorbed. However, the experiment indicates rather complete absorption in a relatively short length. Similar effects have also been observed in work by Budinkov et al.[7], who investigated electron-cyclotron heating of a plasma in a waveguide. This situation can be understood on the basis of some recent work by Bogdankevich and Rukhadze[8] who investigated the absorption of electromagnetic waves in a gyrotropic waveguide. It is shown in this work that both waves, which can appear in a plasma, are found to be coupled to each other by the single boundary condition; in the region of cyclotron resonance strong absorption of both waves occurs. As the radius of the waveguide is extended to infinity one of these waves becomes the ordinary wave and the other becomes the extraordinary wave. On the other hand, as the transverse dimensions of the waveguide are reduced the absorption of the ordinary wave increases and for waveguide dimensions that are comparable with the wavelength the ordinary wave is absorbed as effectively as the extraordinary wave.

4. ELECTRON HEATING AND THE EFFECT ON PLASMA CONFINEMENT

The measurements reported here show that under resonance conditions within the chamber it is possible to achieve total absorption of the microwave power introduced into the plasma. In this case, during the time of the microwave pulse there is no noticeable loss of electron energy in ionization and excitation and all of the absorbed energy is converted into electron kinetic energy (because in the present case for the measured pressures of the neutral gas in the stellarator chamber the characteristic ionization time is approximately 200 μsec). In accordance with these estimates the length of the microwave pulse in the experiment has been made equal to or less than 20 μsec. The microwave measurements indicate that during this time the mean plasma density in the trap is not increased. At the same time the probes indicate a sharp rise in the ion current during the heating pulse. It is well-known from probe theory that the magnitude of the ion saturation current is proportional to the product $n\sqrt{T_e}$, so that heating of the electron component of the plasma should lead to an increase in the probe signal.[4)]

In Fig. 5 we show the variation of the probe signals in time as a function of the power in the heating pulse. It will be evident from the behavior of the probe signals that the electron energy increases throughout the entire heating pulse. The heating increases approximately in proportion to the generator power. The probe measurements could be carried out only for relatively low energy input.[5)] Since the absorption of the microwave

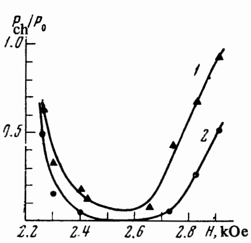

FIG. 3

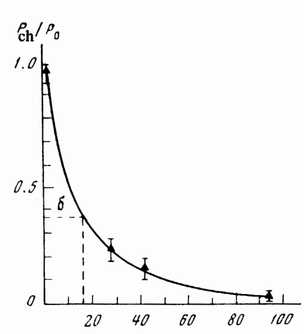

FIG. 4

FIG. 3. Curves showing the absorption of microwave power as a function of magnetic field. The distance from the point at which the microwave power is introduced is as follows: curve 1 – 27 cm, 2 – 94 cm.

FIG. 4. Distribution of microwave power density over the length of the chamber, $H_0 = 2.4$ kOe.

[4)]In probe theory one usually assumes a Maxwellian destribution of electron velocities. When electron heating by an electromagnetic wave at the electron-cyclotron frequency occurs there is primarily an increase in the transverse energy of the electrons. Hence, in the present case by T_e we are to understand some mean characteristic kinetic energy of the electrons.

[5)]At a mean electron energy $\geqslant$ 100 eV the probe measurements become very difficult because of a number of secondary effects.

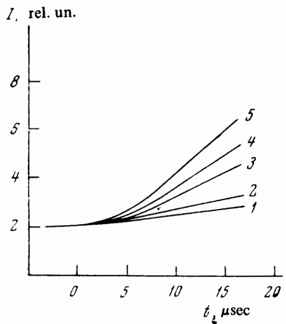

FIG. 5. Curve showing the time variation in ion saturation current to the probe during the heating pulse for various microwave power levels: 1 – 250 W, 2 – 400 W, 3 – 600W, 4 – 1kW, 5 – 1.8 kW.

power occurs in a small region within the stellarator chamber the heating of the plasma electrons is not uniform. The nonuniformity in the heating is associated primarily with the inhomogeneity of the magnetic field over the cross-section of the chamber. Regions in which the resonance condition is satisfied and in which intense electron heating occurs are located along lines of constant magnetic pressure as given above in Fig. 2.

In a straight stellarator the line $|\mathbf{H}|$ = const represents helical surfaces which, when intersecting a plane perpendicular to the stellarator axis, form hyperboli with asymptotes that go through the axis. (The quantity $|\mathbf{H}|$ is equal to H_0 at the asymptotes.) The toroidal geometry leads to some distortion of this pattern. As before, the lines $|\mathbf{H}|$ = const represent helical surfaces but their cross-sections with the meridian plane (Fig. 2) are not, strictly speaking, hyperbolic curves. The asymptotes are displaced from the axis of the torus and correspond to large or small magnitudes of magnetic fields depending on the position of magnetic surfaces in a given cross-section. It will be evident from the curves in Fig. 2 that when the rotational transformation is introduced uniform heating over the entire cross-section will occur only when $H_{res} \sim H_0$. When $H_{res} \lessgtr H_0$ the heating occurs in some annular region, the radial size of which is determined by the relative deviation of H_{res} with respect to H_0.

If we consider only the transiting electrons[9] it can be assumed that the heating occurs approximately uniformly over the entire length of the system in spite of the fact that the absorption of microwave power occurs over a relatively limited length. This result is associated with the fact that the transit time for the entire length of the stellarator chamber for even the odd electrons T_e = 5–10 eV in the plasma before the generator is turned on is much smaller than the length of the microwave pulse; hence, heated electrons are continually leaving the heating region. On the other hand, new particles from the entire chamber volume are continually entering this region. Furthermore, the increase in the transverse component of the particle velocity can lead to an enhancement of the number of trapped particles[9], the drift velocity of which along the axis of the torus will be much smaller than the thermal velocity. These particles will appear in the heating region for a time period comparable with the length of the heating pulse and this provides an additional deviation from uniformity in the heating over the length of the torus.

As we have already indicated, following the injection of plasma into the trap there is established fairly rapidly a uniform distribution of plasma density which does not change appreciably later on. In this case the temperature does not vary appreciably over the cross-section and an equilibrium distribution of plasma pressure is established inside the stellarator. Because of the nonuniform absorption of microwave power and the nonuniform heating the electron-cyclotron heating will disturb this distribution. Under these conditions both longitudinal and transverse temperature gradients appear.

In Fig. 6 we show the distribution, over the chamber diameter, of the ion saturation current to the probe at various times. It is evident from curve 2 that during the microwave pulse there is approximately a 10-fold heating of the electrons; however, the heating is not uniform. The shape of curve 2 is appreciably different from the shape of the initial distribution 1. The existence of additional temperature gradients must lead to an increase in the transverse diffusion and the nonuniform distribution of plasma pressure is relaxed relatively rapidly to the original equilibrium distribution.

As is evident from curves 3 and 4 in Fig. 6, a distribution which is approximately similar to the distribution of the plasma density before heating is established fairly rapidly (approximately 50 μsec). These curves also indicate a sharp reduction in the probe signal after the microwave pulse is switched off. Since the cooling of the electrons is a slow process it is proposed that this reduction is due primarily to the drop in density of the plasma due to diffusion. This result is corroborated by measurements of the plasma lifetime.

The investigation of the effect of electron heating on the plasma lifetime is carried out by means of microwave methods. Furthermore, starting at some instant of time after the heating is terminated, when the distribution of probe current over the cross-section is established and does not vary greatly in the subsequent time, it is also possible to carry out measurements by means of the probes. The result of these measurements are

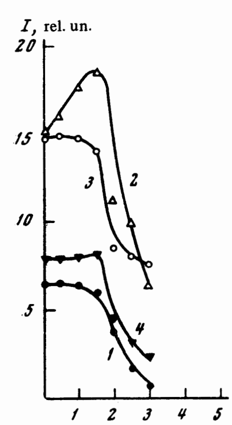

FIG. 6

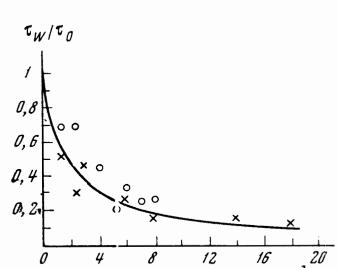

FIG. 7

FIG. 6. Radial distribution of the ion saturation current to the probe at various times Δt after the termination of the heating pulse (W = 3.2 MJ, the length of the microwave pulse T_{mw} = 8 μsec): ● – before heating, Δ – Δt = 2 μsec, ○ – Δt = 12 μsec, ▼ – Δt = 50 μsec.

FIG. 7. The plasma lifetime as a function of the energy of the heating pulse: X – probe measurements, ○ – microwave diagnostics, τ_0 – plasma lifetime before heating.

shown in Fig. 7. Along the abcissa axis we have plotted the energy absorbed in the plasma and along the ordinate axis we have plotted the ratio of plasma lifetime (reduction of density by a factor of e) with resonance electron heating to the initial lifetime of the unheated plasma as obtained by microwave and probe measurements. The microwave energy is varied by varying the generator power for a fixed pulse length and by varying the pulse length (from 2 to 20 μsec) for a fixed power. It will be evident that the plasma lifetime is reduced as the absorbed energy increases, that is to say, as the heating of the plasma electrons becomes stronger.

As we have indicated above, in this series of experiments the effect of additional ionization need not be taken into account. We have also carried out experiments with long microwave pulses (800–1000 μsec). During this time the additional ionization of the neutral gas by the heated electrons becomes important. The experiments show that for low microwave powers there is actually an increase in the plasma density. However, as the generator power is increased the rate of transverse diffusion increases and starts to exceed the rate of gas ionization, leading to a complete disappearance of the plasma during the time in which the microwave pulse is applied. This result has been corroborated both by microwave and probe measurements and by measurements of the integrated emission from the plasma. This effect is reminiscent of the well-known "pump-out" effect which is observed in stellarators when ohmic heating is used.[10]

The experiments reported here still do not make it possible to draw definite conclusions as to the nature of the anomalous plasma diffusion. It will be evident that as the electron temperature increases there is an increase in the plasma diffusion rate, that is to say, there is a dependence opposite to that which would be expected for classical collisional diffusion. At the present time it is still not clear whether this dependence of the diffusion coefficient on temperature is a general property of stellarator systems and whether it obtains for confinement of a plasma injected from outside. It is possible that this dependence appears only as a result of electron-cyclotron heating, which could cause nonuniform heating of the plasma, the appearance of strong temperature gradients, or the appearance of an anisotropy in the velocity distribution which, as is well-known, can lead to the possibility of plasma instabilities.

5. CONCLUSION

Experiments carried out on the L-1 stellarator have indicated the possibility of effective absorption of microwave power in a nonuniform stellarator field under electron-cyclotron resonance conditions. The wave absorption, and consequently the electron heating, are local in nature. The lifetime of the plasma in the system is reduced as the electron heating is increased.

In conclusion, the authors wish to thank M. S. Rabinovich for his interest and support and A. A. Rukhadze for many valuable discussions of the results. The authors are also indebted to P. F. Kozlov and O. I. Nazarenko for help in carrying out the experiments.

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