ON THE PARAMETRIC CYCLOTRON HEATING OF A TOROIDAL PLASMA

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ABSTRACT

The possibility of heating the ionic component of a dense plasma at the parametric cyclotron resonance, using a section of the conducting toroidal chamber of a large scale Tokamak as a resonance cavity, is considered. It is suggested to use the mode TE_{011} to overcome the difficulties with the penetration of HF fields into such a dense plasma. The experimental investigation of parametric cyclotron heating of electrons in a overdense plasma ($n / n_{cut\ off} = 10^2$) on such a model has given hopeful results.

PARAMETRIC CYCLOTRON HEATING IN A TOROIDAL SYSTEM

Let us consider a section of the toroidal conducting chamber limited by two diaphragms (Fig.1a). Such a cavity resembles in shape to a cylindrical one (Fig.1b). As it was shown in /1/, the electrodynamic properties of the cavity (a) differ very little from that of the cavity (b) if $a / R \ll 1$ (where R is the major radius of the torus). So we will consider the cavity (b) taking into account that it forms a part of the torus. We shall also assume that $a \sim l$. Then the condition for the nearness of the toroidal cavity to a cylindrical one is $l / R \ll 1$.

Of all the different types of the oscillations which can be excited in such a cavity, we are interested only in the type TE_{011} the advantages of which, from the point of view of the suggested mechanism for plasma heating, are enumerated below. The configuration of the fields of the TE_{011} type in a cylindrical cavity is shown in fig.2a and is given by

$$E_r = 0 \quad , \quad E_z = 0 \quad , \quad b_\varphi = 0$$
$$E_\varphi = A_1 J_1 (3.83 \tfrac{r}{a}) \sin \tfrac{\pi z}{l}$$
$$b_r = A_2 J_1 (3.83 \tfrac{r}{a}) \cos \tfrac{\pi z}{l}$$
$$b_z = A_3 J_0 (3.83 \tfrac{r}{a}) \sin \tfrac{\pi z}{l} \qquad (1)$$

where A_1 , A_2 and A_3 are constants depending upon the frequency and intensity of oscillations and also on the radius of the cavity, J_1 and J_0 are first and zero order Bessel's functions. As seen from eqn.(1), the electric field in this type of oscillations is purely rotatory and its lines are circles concentric with the cavity, whereas the magnetic field has its maximum at the central portion of the cavity and is directed along Z (Fig.2a). If the plasma is situated in the cavity as shown in fig.2b, then the total magnetic field along Z axis in the central portion of the plasma column is given by:

$$B_z = B_0 (1 + h \cos \omega t) \qquad (2)$$

where $h = b_z / B_0$. (3)

As described in our earlier work /2/, in this case the magnetised charged particles are oscillators with the fundamental resonance frequency

$$\omega_{res.} = 2 \omega_{ck} \qquad (4)$$

where 'k' stands for the kind of the particle. In such a case the transversal energy of the particle, averaged over the initial phases of rotation, grows with time according to the hyperbolic cosine function:

$$W(t) = W_0 \,\mathrm{ch}\,(2 \varkappa t) \qquad (5)$$

After sufficient time from the initial moment ($t \gg \frac{1}{2\varkappa}$) the energy of the particle increases exponentially,

$$W(t) = \frac{1}{2} W_0 \exp (2 \varkappa t) \qquad (6)$$

The growth rate in the considered configuration of fields, at small distances from the axis ($\frac{r}{a} < 0.5$), is given by

$$\varkappa \mp h \omega_{ck} (3.83 \tfrac{r}{a})^2 \left[32 - 8 (3.83 \tfrac{r}{a})^2\right]^{-1} \qquad (7)$$

For example, when $\frac{r}{a} = 0.4$ then $\varkappa = 0.15 h \omega_{ck}$.
Taking $\varkappa = 0.1 h\omega_{ck}$ for the characteristic value of the growth rate, it is seen from (6) that the energy of the particle increases by an order when the number of cyclotron rotations is equal to $N = 15 / h$. If $B_0 = 50$ KGs and $b_z = 50$ Gs. then $h = 10^{-3}$ and the ions of deuterium increase their energy by ten times during $1.5 \cdot 10^4$ cyclotron rotations i.e. in about 60 μ sec.. Thus, the proposed mechanism for heating ions at the parametric cyclotron resonance is quite effective. In this case, the frequency of HF field is $\omega = 2\omega_{ck} = 4.8 . 10^8$ rad./sec., which corresponds to a wavelength in freespace $\lambda_0 = 3,92$ M.
In a waveguide of radius 'a' the wavelength of the mode TE_{011} is

$$\lambda = \lambda_0 \left[1 - \left(\frac{\lambda_0}{1.64 a}\right)^2 \right]^{-\frac{1}{2}} \qquad (8)$$

It can be seen from above that the radius of the cavity cannot be less than 2.4 M. In general the radius should satisfy the inequality,

$$a\ (cm)\ .\ B\ (Gs)\ >\ 1.2\ .\ 10^7 \qquad (9)$$

From relation (9), it is clear that this method of heating can be used only for large scale Tokamaks like T-20 or bigger. With the static magnetic field equal to 50KGs, the inner radius a = 3M the wavelength is equal to 6.5 M and the length of the cavity should be l = 3.25M. i.e. the cavity occupies just a small part of the torus. This enables, in case of necessity, the simultaneous use of few cavities in different parts of the toroidal chamber.

While using the parametric cyclotron resonance for ion heating there arises the problem of penetration of the HF field ($\frac{\omega}{2\pi} \sim 100$ MHz) into a dense plasma. The two main reasons which can hinder the penetration of HF field into plasma are the polarisation effects and the skin effect.

In principle, the configuration of the fields in the cylindrical cavity excited at TE_{011} is the most advantageous one to minimise the effect of both the mentioned reasons. This is because the lines of electric field is always perpendicular to the lines of the static magnetic field, the fact which evades the formation of skin current, i.e. the wave of this type in the given geometry should not feel the skin effect. On the other hand, the electric field lines are concentric to the plasma coloumn and so the plasma is homogeneous along every field line. Hence the polarisation effects which make the plasma opaque when $\omega^2 < \omega_{pe}^2 = \frac{4\pi e^2 n}{m}$ are not considerable. In this connection, there arises the necessity for the experimental investigation of the penetration of HF field of the mode TE_{011} into a plasma with the density lower as well as much higher than the critical density, corresponding to the cut off density.

EXPERIMENT ON PARAMETRIC CYCLOTRON HEATING OF A PLASMA WITH OVERCRITICAL DENSITY

The idea of the experiment consists in observing the behaviour of TE_{011} mode in a cylindrical cavity into a plasma beam whose density could be varied in a wide range of values from $\frac{n}{n_{cut\ off}} < 1$ until $\frac{n}{n_{cut\ off}} \gg 1$ ($n_{cut\ off} = \frac{\omega^2 m}{4\pi e^2}$). The aim of the experiment was to register the parametric cyclotron heating of plasma for all densities. For the parametric cyclotron heating of the ions we need very strong fields in large volumes (formula(9)) characteristic only for large reactors, and not feasible in laboratory experiments. We fulfilled the necessary conditions for the parametric heating for the electrons (not for the ions) which in principle is the same as it is based on the same physical mechanism. However, in the case of resonance for the electrons the condition (9) is much more feasible for the laboratory conditions:

$$a\ (\mathrm{cm}).\ B\ (\mathrm{Gs}) \quad > \quad 3.2\ .10^{3} \qquad (10)$$

The parameters of our experiments, a = 11.4 cm., B = 430 Gs. and l = 9 cm., satisfy this condition.

EXPERIMENTAL DEVICE

A cylindrical plasma beam with diameter 2cm. with the longitudinal ionic energy upto several hundreds eV and the ionic current upto 3 amperes was produced by a reflex discharge source, where the pressure $\sim 10^{-3}$ torr. was maintained by a regular injection of Argon. The plasma from the source entered the chamber where the dynamic pressure lay in the interval $(1-5).10^{-4}$ torr. In this region, just before entering the cavity, the plasma density was measured with the help of an 8mm. interferometer. The source could provide densities lying in the range $(2.10^{10}-5.10^{12})\mathrm{cm}^{-3}$ (we cite the peak values at the axis). For densities upto $1.10^{11}\ \mathrm{cm}^{-3}$ an electrostatic probe was used to measure the density. However, for $n > 10^{11}\ \mathrm{cm}^{-3}$ the probe got heated upto a temperature 2000°C and the determination of the ionic current became impossible due to thermal emission of electrons. When the probe was oriented perpendicular to the magnetic field it got destroyed completely by plasma of density $n > 10^{12}\ \mathrm{cm}^{-3}$. Therefore, the probe was oriented along the magnetic field and used only for the determination of the potential of the insulated probe $\varphi_{ins.pr}$ which depends on the electron temperature. After passing through the horns of the interferometer, the plasma entered the cylindrical cavity and travelled further. The homogeneous magnetic field in the region of the cavity could be varied from 0 to 1300 Gs.. The electrostatic probe was placed inside the cavity and could be moved both along the radius as well as the length of the cavity. The measurements showed that the probe practically did not affect the field distribution in the cavity. The longitudinal energy was registered with the help of a multigrid electrostatic analyser (not shown in the figure) when the density was not higher than 5.10^{10} cm.$^{-3}$. The cavity was excited with the help of a loop placed in the central plane of the cavity. Special measures were taken to avoid the excitation of other modes. The HF generator was frequency modulated by less than 1% with a frequency 100 Hz, as a result of which the HF interaction with plasma was pulsed and enabled us oscillographing the processes. The measurements showed that when the power of the HF generator was 100 Watts, the empty cavity absorbed $P^{o}_{cav} = 75$ Watts. The value of b_z at the central plane of the cavity (Q = 7000) reached upto 2.3 Gs.i.e. $h = 5.10^{-3}$, which corresponds to an average value of the growth rate $\bar{æ} = 10^{5}$ sec^{-1}. Under this condition, the energy of the electron should increase by an order during the time $t^{*} = 1.5 \frac{1}{æ} = 15 \mu$ sec.. The HF energy absorbed by the plasma was measured from the levels of the stored energy in the cavity when it is empty and with the plasma in it. As it turned out (see below), the energy absorbed by the cavity with plasma practically did not differ from the energy absorbed by the empty cavity. Under these conditions, the energy absorbed by plasma during one second is obtained from the formula /3/,

$$P_{pl} = P^{o}_{cav} \left(1 - A_{pl} / A_{0} \right) \qquad (11)$$

where P_{pl} is the power absorbed by plasma, A_{pl} and A_0 - signals proportional to the stored energy in the cavity with plasma and when it is empty correspondingly. The quantities A_{pl} and A_0 were determined with the help of a loop antenna placed at the wall of the cavity. The configuration of the magnetostatic field is shown in fig.3.

EXPERIMENTAL RESULTS

In Fig.4 we see the dependence of the signal registered by the loop antenna on the angle of its rotation relative to the position coinciding with the plane of cross section of the cavity. From the curves it is seen that the shape of the curve corresponding to the mode TE_{011} in an empty cavity remains unchanged even in the presence of a plasma with density $\frac{n}{n_{cut\ off}} < 1$ as well as $\frac{n}{n_{cut\ off}}$ 1, and there is no tendency to distortion of the fields with the increase of $n / n_{cut\ off}$.

As said above, an insulated probe was used to register the plasma heating. It's potential is equal to

$$\varphi_{i.p} = \varphi_{pl} + \varphi_{fl} \tag{12}$$

where φ_{pl} - the plasma potential at the given point, φ_{fl} - the floating potential equal to $\varphi_{fl} = \mathrm{const}.\overline{W}_e$, where $\overline{W}_e$ is the mean energy of the electrons. Since in parametric heating there is no stationary charge separation and also as a result of the fact that the diffusion in a direction perpendicular to the magnetic field is made difficult, φ_{pl} is almost a constant during electron heating, whereas φ_{fl} remains proportional to $\overline{W}_e$. Therefore, the change in the potential of an insulated probe in the first approximation is given by:

$$\Delta\varphi_{i.p} = \Delta\varphi_{fl} \sim \Delta\overline{W}_e \tag{13}$$

Thus the quantity $\Delta\varphi_{i.p}$ characterises the electron heating. The values of $\Delta\varphi_{i.p}$ at different points along the radius of the plasma beam (when $n / n_{cut\ off} = 26$) is given in fig.5. It is seen from fig.5 , that the electron heating takes place all over the cross section, while the additional ionisation of the neutral gas by the HF field outside the plasma is not considerable ($\Delta\varphi_{i.p}$ outside the beam is much less than inside). From this it follows that, even when the density is much more than the cut off value, the HF field penetrates right to the centre of the plasma beam. The classical skin layer in this case is about $\delta = \frac{c}{\omega_{pe}} = 3$mm., which is 3 - 4 times less than the plasma radius. The decrease in heating at the centre in comparison to the periphery is explained by the fact that within the limits of the plasma beam, the energy growth rate increases towards the periphery (see formula (7)). Such a slight decrease in heating at the centre takes place for all densities, both $\frac{n}{n_{cut\ off}} < 1$ as well as $\frac{n}{n_{cut\ off}} \gg 1$ and is connected with neither polarisation effects nor the skin effect. The radial distribution of $\Delta\varphi_{i.p}$ was obtained for 8 different values of densities. It was noticed that, while the shape of the distribution curve remains almost the same, the level goes down with the increase in density. This is seen from fig.6. It is to be noticed that, the decrease in heating takes place in such a way that within the limits of the experimental accuracy $nT = const.$. This is explained by the fact that the HF energy absorbed by the plasma is redistributed amongst the increasing number of particles. However, such a situation is possible only in the case, when the amount of HF energy absorbed by plasma does not depend upon the density as was noticed in our experiments (see fig.7). These results were obtained with the help of measurements of the coefficient of standing waves in the HF tract and the levels of stored energy in the cavity (see formula (11)).

CONCLUSIONS

The experimental results seem to be confirming the views expressed in the first part of this paper. The parametric cyclotron heating of electrons was reliably registered even in a plasma where the HF field should not penetrate normally. We could succeed in reaching upto the region where $n / n_{cut\ off} = 10^2$ and the ratio of the classical skin layer to the radius of the plasma beam $\frac{\delta}{r} = 0.18$, and in all cases the heating was registered right till the centre of the plasma beam. However, the experiments need to be extended for much higher parameters, $n/ n_{cut\ off} = 10^6$ and $\frac{\delta}{r} = 3.10^{-4}$, characteristic for large scale machines.

REFERENCES

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Fig. 1

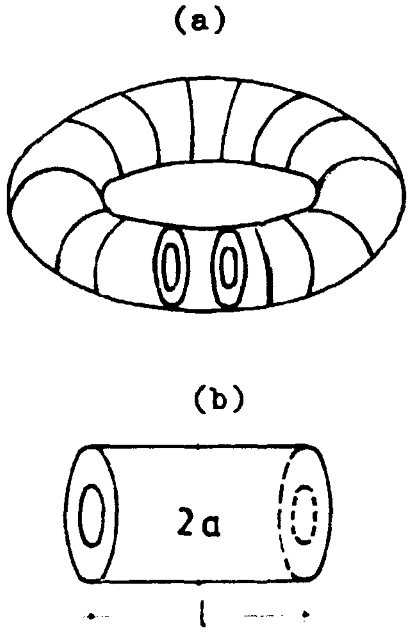


Fig. 2

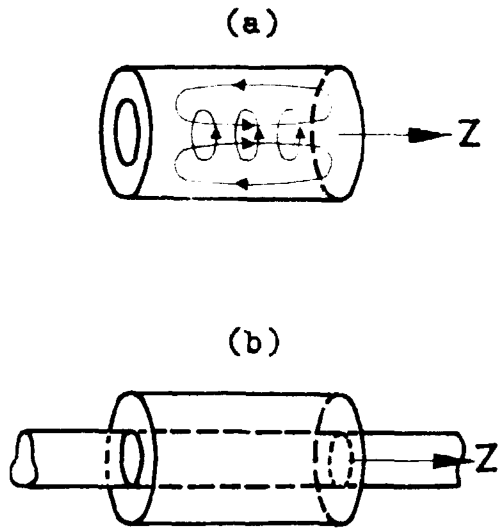


Fig. 3

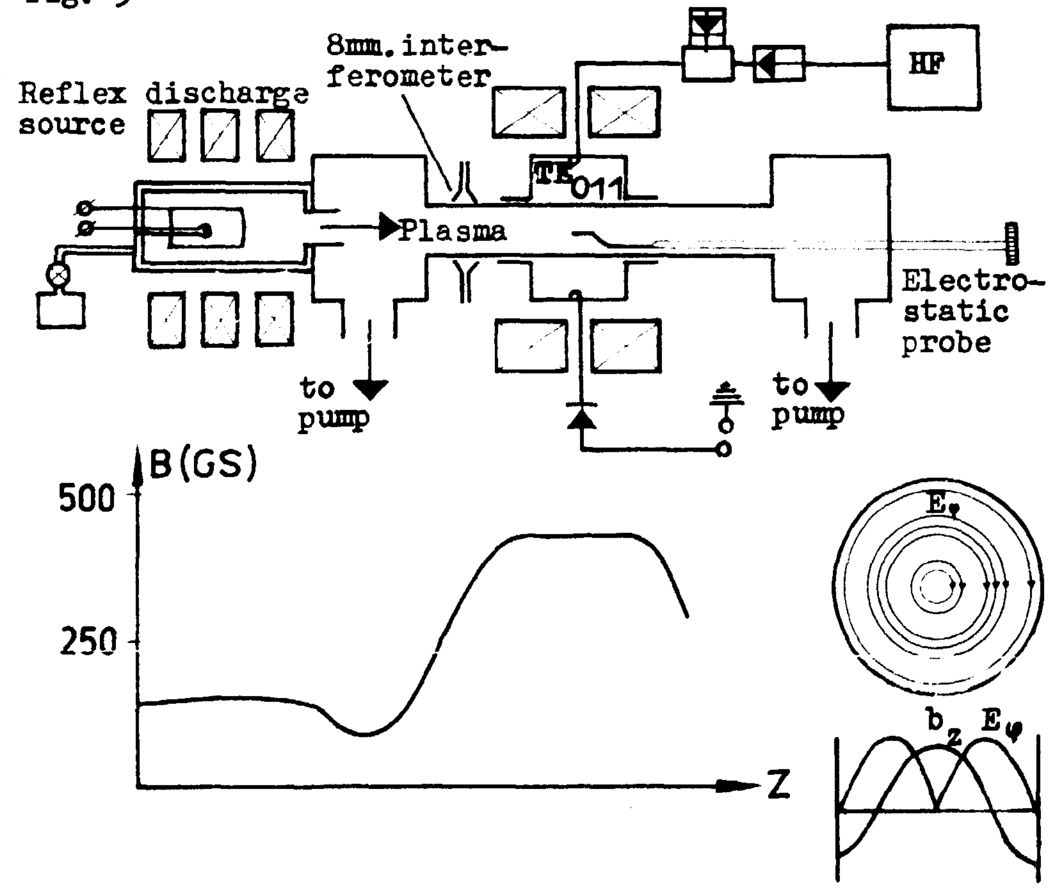
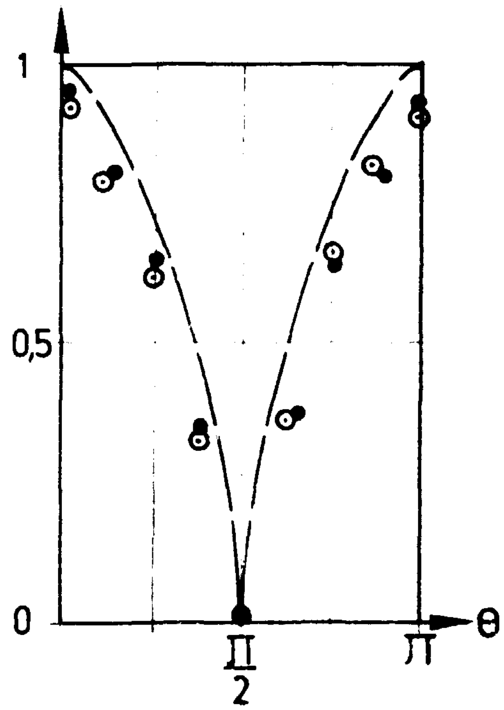


Fig. 4



— — empty cavity
⊙⊙⊙ $n = 6{,}10^{10}$ (cm^{-3})
●●● $n = 5.10^{12}$ (cm^{-3})

Fig. 6

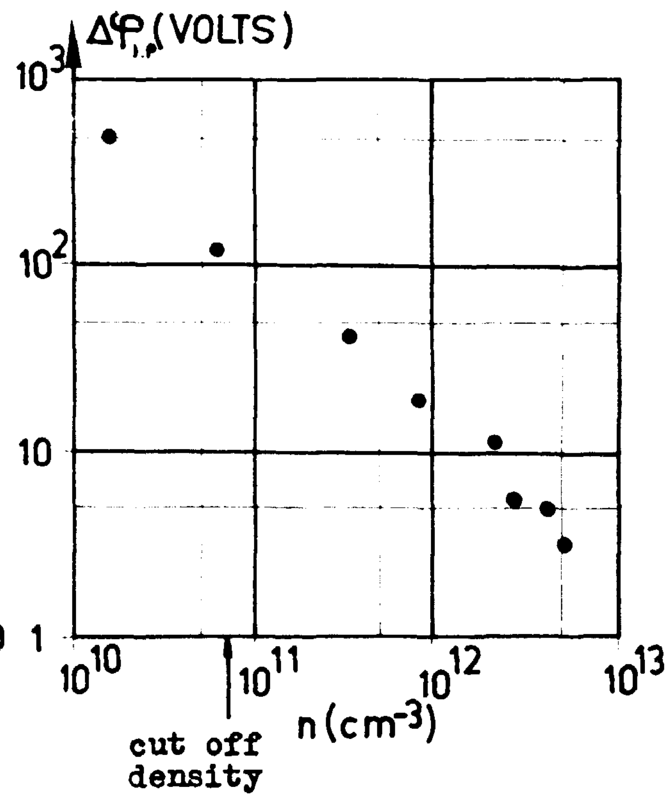


Fig. 5

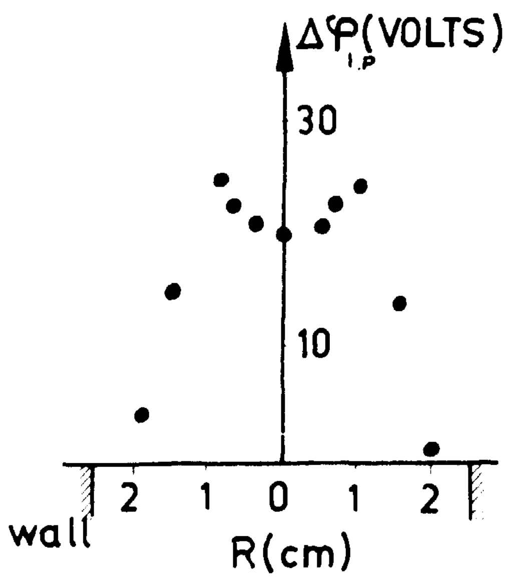
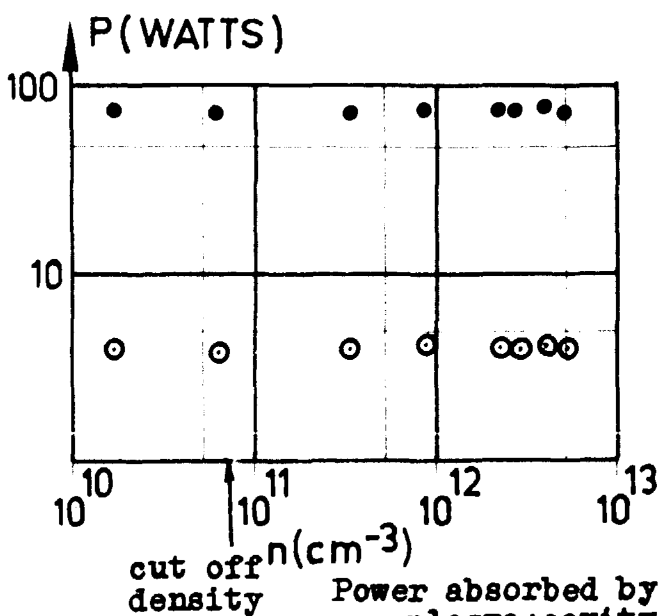


Fig. 7



Power absorbed by
●●● plasma+cavity
⊙⊙⊙ plasma alone