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THE PRODUCING OF AN ECR PLASMA USING 2450MHz WHISTLER WAVE AND THE INVESTIGATING OF ITS PARAMETERS *

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ABSTRACT

A stable ECR plasma was produced and sustained in HER mirror using 2450MHz Whistler wave. The parameters of the ECR plasma and their chaining characters were studied in detail and were compared with those of the DC discharge plasmas. The conclusion is that the ECR plasma is a high ionizability, low temperature, middle density plasma, its peak density may much exceed the cutoff density of the pump wave (when $\omega = \omega_{pe}$) and arrive at the order of $10^{12}cm^{-3}$. The ECR plasma includes some high energy hot electrons (20Kev-200Kev) and middle energy warm electrons (< 20Kev). Those two kinds of electron created some strong X-ray emissions in a wide frequency range. The ECR plasma has higher edge density and can strongly interact with the wall.

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I. Introduction

Using the waves with high frequency, moderate power, we can ionize the neutral gas in magnetic fusion devices by means of the electron cyclotron mechanism, and produce some initial plasmas with certain temperature and density. This method is the ordinary method used in varied fusion devices. For example, in the start up phase of the Tokamak discharge, using ECR pre-ionized method, the rise speed of plasma current can be accelerated, and so the Volt-Second number can be saved [1,2]. The method of ECR ionization also used to form the initial plasma in magnetic mirrors and the target plasmas for N.B.injection.[3]

In recent years ECR plasma is used to clean the vacuum vessels of varied devices. The result is better than the general method, DC discharge method. The ECR method can not only remove the light impurities which attach to the wall. but also remove the water effectively. This method has been considered a good one for cleaning [4.5]

Since one or two years ago, ECR method has played an important role in material research which is used in the fusion reactors. Using the strong interaction between ECR plasmas and wall, a kind of film of certain material can be formed on the wall, and such film can make the wall satisfy the need for fusion reactors [6].

So it is very important to study the ECR plasma itself.

We used a 2450MHz Magnetron launcher to produce the Whistler Wave in the HER mirror. This wave produced and heated the ECR plasmas and we investigated the parameters and the changes of this plasmas, compared it with the DC plasmas. The results are very interesting.

In section 2, we will give the device and experimental arrangement. Section 3 gives a rough theory of the exciting, transmission and absorption of the waves. Section 4 will give the experimental results and some discussion is given in Section 5.

2. The device and the Experimental Arrangment

The experiment is carried out in HER Mirror device.[7] This device is an axisymmetric simple mirror. Its parameters are:

L(Mirror to Mirror)	60cm(changable)
R_o(the radius of the vacuum chamber)	12cm
R_M(the mirror ratio)	1.5-4(changable)
B_{max}	2.5-3 T.(pulse)
	0.25-0.3 T (DC)

Use a Magnetron launcher to inject the microwave into the mirror device through its end window. The power of the wave is about 0.5–5KW. and the transmitter and antenna are the regular waveguides with dimension 12cm. The microwave window is made of PTFE (polytetrafluoroethylene). The H_{10} Mode wave was injected into the device through this window. If the magnetic field is suitable the wave is in cyclotron resonance with the free electrons which were accelerated and ionized the gas(H_2) and the plasma was formed.

In the experiment, we used several diagnostic methods, they are:

- 8mm microwave interferometer, to measure the plasma average density.
- Movable probes in the radial direction, to measure the plasma density and electron temperature and their radial profile.
- Monochromator, to measure the intensity of varied lines which were launched from the plasmas, (for example H_α, H_β ...).
- The hard X-ray detector at higher energy rang, to measure the intensity of X-ray emission(20Kev–600.Kev) from the plasmas.
- The hard X-ray detector at lower energy rang, to measure the intensity of X-ray emission from the plasmas. (5Kev–20Kev). And these two kinds of detectors can count the numbers of the X-ray photons.

In this experiment, there is a DC power supply and an electrode in the vacuum chamber, so that it is very convenient to produce the DC discharge plasmas.

The arrangment of this experiment is shown in Fig.I.

3. The exciting, transmission, and absorption of waves

The 2450MHz H_{10} wave was transmitted in rectangular waveguide and was launched by the rectangular waveguide also. The wave passed through the microwave window into the chamber. This kind of antenna can make the wave to form the "pencil beam". So, in our experiment the wave transmitted approximately parallel to the magnetic field.

In the frequency rang of $\omega \sim \omega_{ce}$, the transmission of waves should satisfy the Appletron-Hartree dispersion relation, (8)

$$N^2 = 1 - \left[2\alpha\omega^2(1-\alpha)\right] / \left[2\omega^2(1-\alpha) - \omega_{ce}^2 \sin^2\theta \pm \omega_{ce}\Delta\right] \qquad (1)$$

Where,
$$\alpha \equiv (\omega_{pe}^2 + \omega_{pi}^2)/\omega^2 \simeq \omega_{pe}^2/\omega^2 \qquad (2)$$

$$\Delta \equiv \left[\omega_{ce}^2 \sin^4\theta + 4\omega^2(1-\alpha)^2\cos^2\theta\right]^{1/2} \qquad (3)$$

θ: the angle between $\vec{K}$(wave vector)and $\vec{B}$(magnetic field).

$$N^2 \equiv \frac{c^2K^2}{\omega^2} = \frac{c^2}{V_p^2} \qquad (4)$$

ω_{pe}, ω_{pi}, ω_{ce}, K, N, V_p are the electron plasma frequency, the ion plasma frequency, the electron cyclotron frequency, the values of wave vector, the refraction coefficent of plasmas and the phase velocity of waves respectively.

In the case of quasi longitudinal transmission, the dispersion relation can be reduced to:

$$N^2 \simeq 1 - \frac{\alpha\omega}{\omega + \omega_{ce}\cos\theta} \qquad \text{(QL-L Mode)} \qquad (5)$$

$$N^2 \simeq 1 - \frac{\alpha\omega}{\omega - \omega_{ce}\cos\theta} \qquad \text{(QL-R Mode)} \qquad (6)$$

They are called left-handed wave and right-handed waves respectively.

The characteristics of the transmission and absortion of these waves are:

(I) FOR QL-L Mode:

when $\omega < \omega_{ci}$, be able to transmit, $V_p < c$ slow-wave.

when $\omega = \omega_{ci}$, resonance absorption, $N^2 \to \infty$.

when $\omega_{ci} < \omega < \omega_1$, be not able to transmit, (cut off).

when $\omega > \omega_1$, be able to transmit, $V_p > c$, fast wave.

when $\omega \gg \omega_1$, $V_p \to c$, become ordinary electro-magnetic wave.

(2) For QL-R Mode:

when $\omega < \omega_{ce}$, be able to transmit, $V_p < C$, slow wave.

when $\omega = \omega_{ce}$, resonance absorption, $N^2 \to \infty$.

when $\omega_{ce} < \omega < \omega_2$, be not able to transmit, (cut off).

WHEN $\omega > \omega_2$, be able to transmit, $V_p > C$, fast wave.

when $\omega \gg \omega_2$, $V_p \to C$, become ordinary electro-magnetic wave.

The ω_1, ω_2 are the low density and high density cut-off frequencies respectively. They are:

$$\omega_{1,2} = \mp \frac{\omega_{ce}}{2} + \left(\frac{\omega_{ce}^2}{4} + \omega_{pe}^2\right)^{1/2} \qquad (7)$$

Fig.2 shows the characteristics of the QL waves.

In our experiment, the transmission area was selected the range of $\omega_{ce} \geq \omega$, so that the component of left handed wave is the fast wave, which would transmit through the plasmas and out of it through the window at the other end. But the component of right wave is the Whistler wave, it can transmit in the plasmas and when it goes into the area of $\omega = \omega_{ce}$, it will be absorbed strongly by the plasmas.

From Eq.(6), we see that the transmission of the Whistler wave depends on the magnetic field only and is not related to the plasma density. So the Whistler wave can be used to heat the plasmas which have lower parameters. Because the magnetic field of mirrors is opened, it is convenient to use the Whistler wave to heat the mirror plasmas.

4. Some results of the experiment

At different experiment conditions, we measured the plasma parameters, the light emissions and X-ray emissions from plasmas on ECR discharge and DC discharge respectively. The results are interesting and important.

When the $\omega = \omega_{ce}$ layer(B=875G.) exists in the vacuum chamber and the pressure of gas(H_2) is proper, the microwave can produce the ECR plasmas. (Fig.3) From Fig.3, we see that the plasma signals underwent a large rise and fall, it is because the fluctuation of the magnetic field.

Changing the current of the magnetic field, I_M, the positions of each different resonance layers were changed. Fig.4 gave two typical cases. The Fig.4a is the case that the $\omega = \omega_{ce}$ layer is in the middle plane area of the device and the $\omega = 2\omega_{ce}$ layers do not exist in the vacuum chamber. Fig.4b gave another case that the $\omega = \omega_{ce}$ layers are located in the two side areas of the mirror device and the $\omega = 2\omega_{ce}$ layers are in the middle plane area.

4.1 The ECR plasma

(1) The relations between plasma density and magnetic field

Fig.5 shows the relations between plasma density in the periphery and the magnetic field. It shows that when $\omega = \omega_{ce}$ layer is located in the middle area (I_M=250A), the density is the highest, and when $\omega = \omega_{ce}$ is not in the vacuum chamber(I_M is too small or too large), the plasma density n_e, is near zero. In this case, ECR ionizing did not appear.

(2) The effect of gas pressure to the plasma parameters.

A. The change of the plasma density following the gas pressure in different magnetic fields.

Fig.6 shows the change of the plasma density in the peripheral area ($r_p \sim$ 10cm) at two different magnetic field configurations. When the gas pressure is changing. It is very obvious that there exists a best gas pressure range and at different magnetic fields this best range is also different. The difference between the densities in different cases can reach one order.

B. In different radial positions, the tendency of changing of the plasma density is not the same. In lower gas pressure range($P_0 \sim 10^{-4}$ Torr.), the gradient of the plasma density is lower and the plasma density in the edge area is comparatively higher. (in the best condition, it can reach $10^{11} cm^{-3}$ order)

When the pressure rose, the density in the edge area fell down! But in the centre area, the plasma density rose followed the gas pressure. This phenomenon was shown in Fig.7.

(3) The effect of microwave power to the plasma parameters

In a certain gas pressure and magnetic field, change the microwave power and detect the average intensity of H_α emission along the device axis and measure the ion current in the peripheral area by a probe. It is shown that, when the microwave power rises, the intensity of H_α emission becomes stronger too. This phenomenon can be considered that the plasma density in the centre area is rising followed the microwave power. (It is known that the electron temperature did not change very much according the probe signals.) This character was shown in Fig. 8.

But, at the same time we used the probe to mesure the plasma density in the peripheral area. It is shown that when the wavepower rises, the density in this area falls down! It is opposite to that of centre areas. Fig.9 shows this phenomenon.

(4) The X-ray emission from ECR plasma

Use crystal detector, plastic detector respectively to measure the intensities of higher energy hard X-ray emission(15–600Kev) and lower energy hard X-ray emission(5–15Kev) from the ECR plasmas.

A. Higher energy hard X-ray emission(15–600Kev)

The hard X-ray emission from plasmas can reflect the characteristics of the hot electron groups with higher temperature ($T_e \sim$50–200Kev) in plasmas. The temperature and density of the hot electrons can effect the spectrum and the intensity of X-ray emission. This higher temperture hot electrons were formed by ECRH heating in $\omega = 2\omega_{ce}$ area.

From Fig.10, we can know that the hard X-ray emission was corresponding to the existence of plasmas. The emission inteneity $I_x \Delta t$ was effected by the gas pressure and magnetic field. (Fig.11.a,b)

It is shown that the hard X-ray intensity is very sensitive to the gas pressure. In lower gas pressure, the X-ray intensity is stronger.

The positions of the resonance layers also effected the X-ray emission. From Fig.II.b, it is shown that when I_M was in the range of 170A-200A, the hard X-ray intensity was stronger than other ranges. The I_M range of 170-200A was corresponding to the positions that the $\omega = 2\omega_{ce}$ was in the middle plane area. (Fig.4b)

B. Lower energy hard X-ray emission(5Kev-15Kev)

Use a plastic detector to measure the lower energy hard X-ray emission. The lower energy hard X-ray was produced by the middle temperature hot electrons produced by the mechanism of electron cyclotron resonance heating. In our experiment it was shown that this middle temperature hot electrons were formed in the $\omega = \omega_{ce}$ area.

Fig.12 shows that, as the higher energy hot electrons, the lower energy hot electrons correspond to the existing of ECR plasmas too. Fig.I3 gave the changing tendency of the lower energy hard X-ray emission in two different magnetic fields. (250A and 180A) In these two cases, it was shown that the X-ray emissions were sensitive to the gas pressure. When the gas pressure was between 3.5 x 10^{-5}-7 x 10^{-5}Torr., the lower energy hard X-ray emission was the strongest. At higher gas pressure range, the X-ray emission fell down rapidly.

For the magnetic field, the lower energy hard X-ray emission was much stronger in the range of I_M=250A than the range of I_M=I80A. The former corresponds to the magnetic field shown in Fig.4a, and the other corresponds to the Fig.4b.

So, we can obtain the conclusions that the lower energy hard X-ray emission were formed in the fundamental resonance area ($\omega = \omega_{ce}$) by ECRH and the higher energy hard X-ray emissions were formed in the second harmonic resonance area ($\omega = 2\omega_{ce}$) from the higher temperature electrons produced by the ECRH mechanism also.

4.2 The DC plasmas

DC discharge is the ordinary method to clean the vacuum chamber wall.[9] About the DC plasma, there were some detail description. In order to compare the ECR plasma and the DC plasma, the DC discharge was carried out and the parameters of the DC plasmas was measured.

(1) The gas pressure must be higher($5xI0^{-2}$-$7xI0^{-3}$Torr.) for DC discharge.

This pressure is much higher than ECR discharge about 2-3 orders.

(2) There exists a best gas pressure range for DC discharge, too. (Fig.I4) In our experiment, the best pressure was in the range of 2-$3xI0^{-2}$Torr.

(3) The radial profile of the plasma density of DC discharge was generally a parabola. The plasma density in the centre area can reach $IxI0^{I0}cm^{-3}$, which is higher than that in peripheral area. The change tendency of density is the same in whole radial profile. (Fig.I5, I6) It is different from ECR plasma. (see Fig.7)

(4) The relations between the discharge current and the parameters of the DC plasmas,

A. Following the rising of the discharge current, the plasma density n_e rises too. When the discharge current reached 7A, the density began saturating. The saturation phenomenon appeared in the centre area firstly.

B. Following the rising of the discharge current, the electron temperature rises slowly. (Fig.I7)

(5) In any case, there is no X-ray emission from the DC discharge plasma. It is obvious that in the DC discharge plasmas there exists no mechanism which can heat the electrons continuously and make the electrons hotter and hotter as in the ECR plasmas.

(6) From the probe signals, it was known that, the float electric potential of the DC plasmas can reach 200-300V. It attributes to the mechanism of DC discharge. The float potential(V_f) is related to the discharge current and the gas pressure. The existence of this large float voltage formed a strong bombardment to the wall by the ions. This is an obvious character of the DC plasmas.

5. Discussion

5.1 The comparison of the ECR plasma and the DC plasma.

(1) ECR plasma and DC discharge plasma are both low temperature plasmas. The electron temperature of these two kinds of plasma is only several ev.

(2) The parameters of the two kinds of plasma both relate to the gas pressure sensitively. There exist the best gas pressures for the two kinds of plasma. The range of those best gas pressures are:

For ECR discharge, $3x10^{-5}$—$1x10^{-4}$ Torr.

For DC discharge, $2x10^{-2}$—$3x10^{-2}$ Torr.

(3) The density of the ECR plasma is much higher than the DC discharge plasma. At the best gas pressures for both the two kinds of plasmas, the plasma densities are:

ECR plasma, 0.5—1×10^{12} cm^{-3} (centre area).
0.5—2×10^{10} cm^{-3} (edge area).

DC plasma, 1-3×10^{10} cm^{-3} (centre area).
1-3×10^{9} cm^{-3} (edge area).

So the DC discharge plasma is a weakly ionized plasma, for which the ionizability is smaller than 0.1%. But, the ECR plasma is a strongly ionized plasma, the ionizability can reach 2o-5o %.

(4) At lower pressures and suitable magnetic field, ECR discharge can form some higher temperature hot electrons(20—several hundred Kev) and some moderate temperature hot electrons(< 20Kev). These two kinds of hot electrons were produced by different mechanisms respectively. The former is produced in the second harmonic resonance layer by the ECRH mechanism($\omega = 2\omega_{ce}$) and the latter is formed in the fundemental resonance layer($\omega = \omega_{ce}$) by the ECRH mechanism also. The moderate temperature hot electrons just right become the source of the higher temperature hot electrons.

The DC discharge did not produce any hot electrons.

(5) The DC discarge must use an electrode, so its float voltage can reach several hundred volts. This float voltage forms a strong bombardment to the wall. Yet the ECR discharge does not use such electrodes, its float voltage is only several tens volts and its space voltage is about in the several negative tens volts range.(rule out the effect of the probe) So it is not as the DC discharge, the wall does not undergo strong bombardment.

5.2 At suitable discharge conditions, the ECR plasma produced by Whistler wave can emit strong X-ray with wide spectrum band. It is important to study this kind of X-ray source.

5.3 We have formed a stable, very long pulse length(several Min.) hot electron plasmas using the Whistler wave. This plasma can be used as a fundamental condition to study the physical processes of the hot electron plasmas in mirror devices. Such as the plasma instability of the cold and the hot components, the particle and energy transport, the interaction of wave-plasmas, ... could be studied in this stable ECR plasmas.

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FIGURE CAPTIONS

Fig.1 The arrangement of the Whistler Wave ECR Plasma Experiment.

Fig.2 The dispersion relation or $\vec{K}/\!/\vec{B}$, cold plasma simulation.

Fig.3 The saturate ion current detected by probe (r - 10.5cm). The fluctuation of plasmas were because the fluctuation of the magnetic field.

Fig.4 Two different magnetic field configurations and positions of resonance layers. (a) I_M = 250A. (b) I_M = 180A.

Fig.5 The changing tendency of the plasma density in the edge area following the magnetic field. (R_M = 2.1)

Fig.6 The edge plasma density followed the gas pressure (R_M = 2.1, r_p = 10cm).

Fig.7 The plasma density radial profile in two different gas pressures.

Fig.8 The change of the H_α emissions from the plasmas followed the microwave power.

Fig.9 The change of the plasma density near the wall followed the microwave power.

Fig.10 The hard X-ray emission and the H_α emission from the ECR plasmas. (200A, 5 x 10^{-4}Torr. 0.5KW).

Fig.11 The relations between the hard X-ray emission and the gas pressure, the magnetic field.
(a) The curve of $I_x\Delta t \sim P_0$, at different magnetic fields.
(b) The curve of $I_x\Delta t \sim I_M$, at different gas pressure.

Fig.12 The non-continuous hard X-ray emission corresponding the plasmas fluctuation.

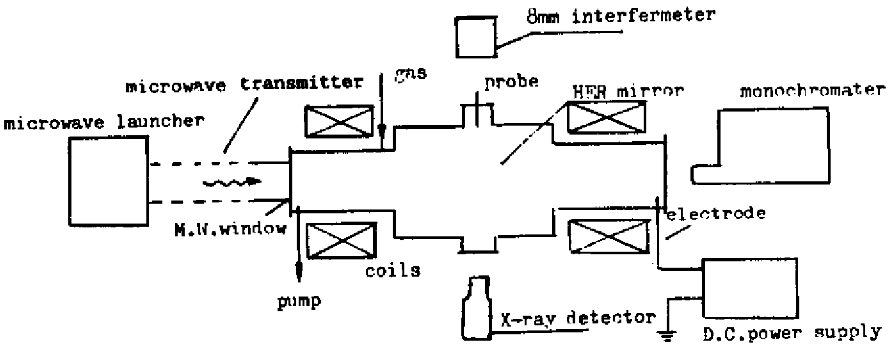
Fig.13 At two different magnetic fields the count of the lower energy hard X-ray changed with the gas pressure ($P_{\mu-}$ = 1KW).

Fig.14 At r_p = 7cm, the density of the DC plasmas changed with the gas pressure.

Fig.15 The radial profile of the plasma density of the DC plasmas.

Fig.16 At different radial positions the density of DC plasmas changed with the gas pressure.

Fig.17 At different radial positions the temperature of DC plasmas changed with the discharge current.



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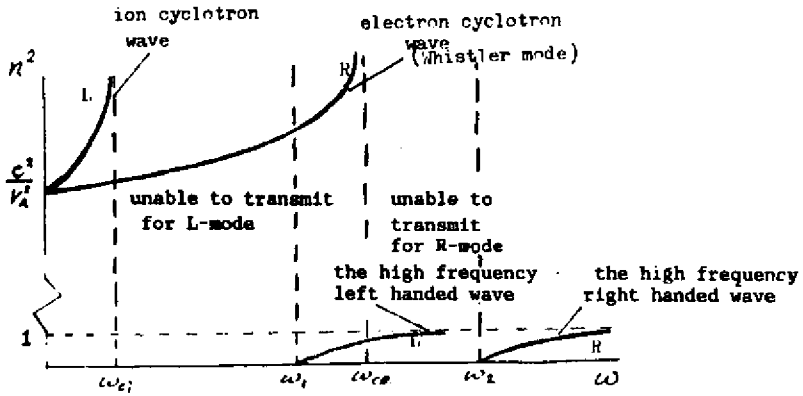

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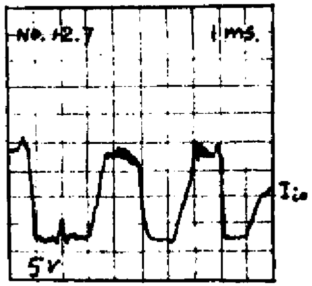

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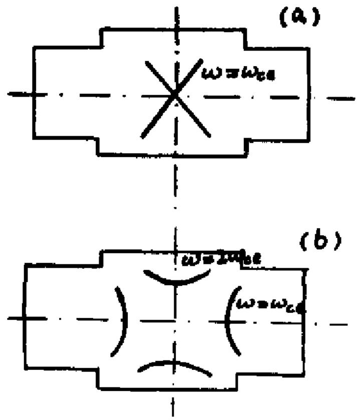

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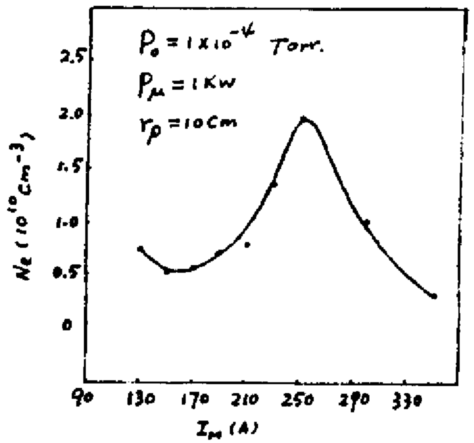

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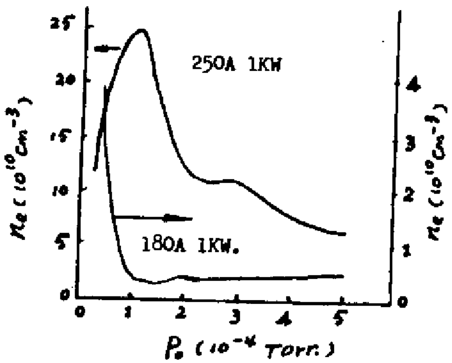

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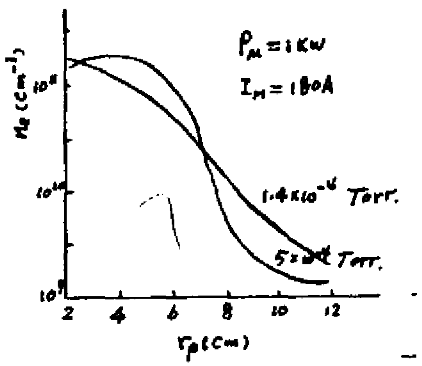

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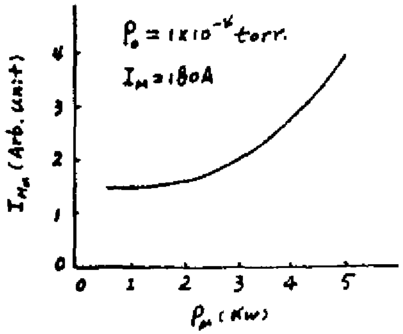

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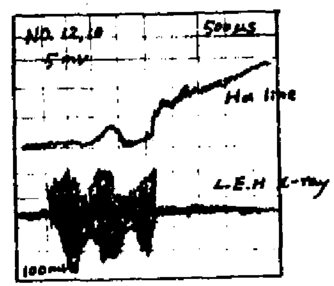

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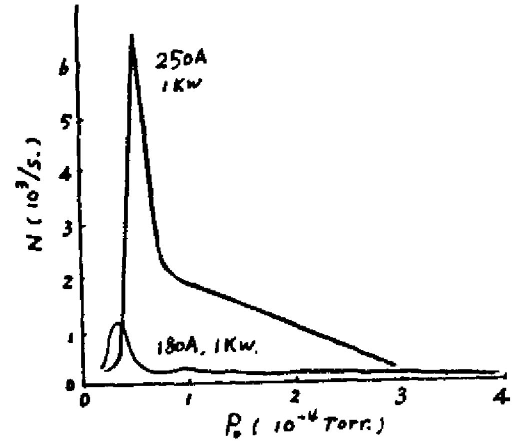

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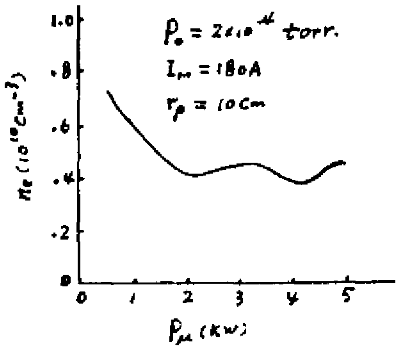

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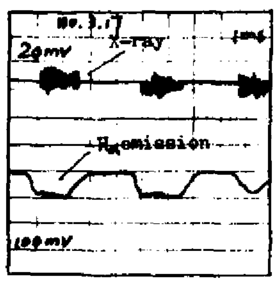

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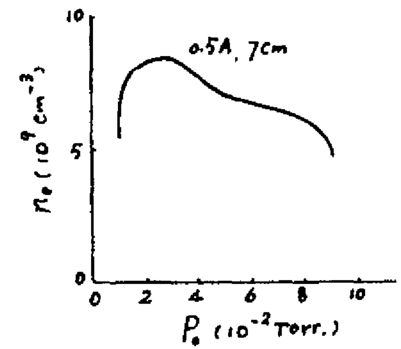

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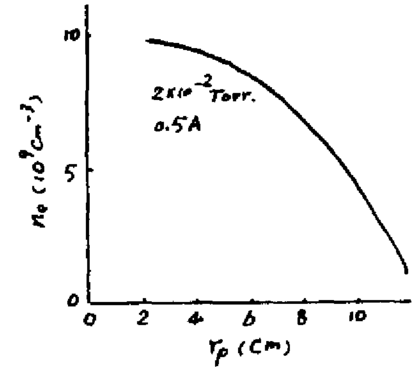

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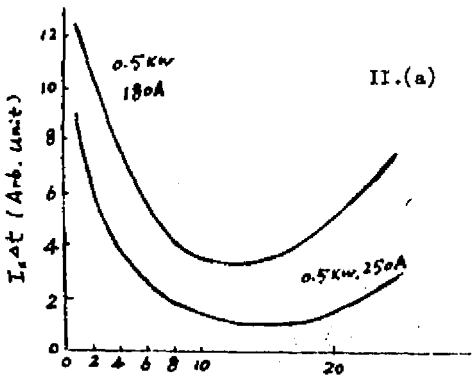

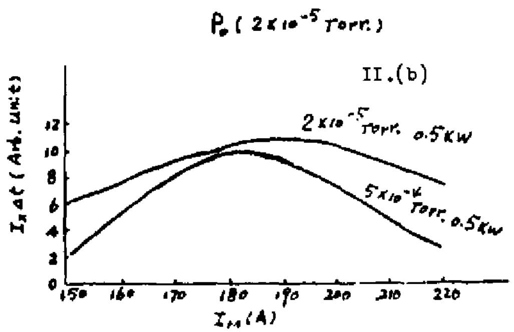

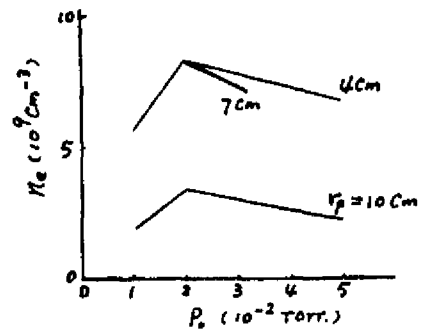

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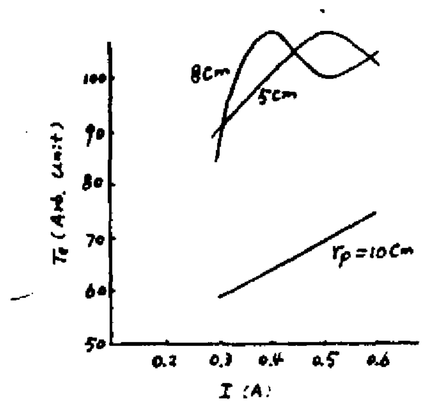

Fig.17