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Measurement of Soft X-ray from Hot Electron Plasma in a Magnetic Field†

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and Yoshiaki AGAWA****

Abstract

Soft X-ray measurement is performed on a hot electron plasma produced by ECR discharge. The measured X-ray energy ranges to 1–15 keV and hot electron temperature and its density are determined in various gas species from this measurement. Efficient coupling of the wave with the plasma at the resonance zone and increasing the power input are clarified to be important for making a plasma to a high temperature state with sufficient emission of soft X-ray. Some differences in the plasma characteristics in various gas species are also described.

KEY WORDS: (ECR Plasma) (Fundamental Resonance) (Soft X-ray) (Hot Electron) (Cold Electron)

1. Introduction

Hot electron plasmas typical for ECR (electron cyclotron resonance) discharge have extensively been studied for many years in the nuclear fusion research[1–3]. Among these studies experiments[4–6] in a simple mirror field have advanced to the application of such a plasma to simply and multiply charged ion sources[7–8]. Recently they are also used as favorable heat sources for the processing of various materials[9–10]. We are interested in the application of a hot electron plasma in various gas species as a plasma X-ray source as well as application to above mentioned processing. We are now studying[11] a high density and high temperature ECR plasma production using a high power 60 GHz Gyrotron. The experiment is performed in a pulsed mode operation, and detailed and precise measurement of soft X-rays emitted from the plasma has now been undertaken.

The measurement of soft X-rays from a plasma usually needs many careful preparation and checking procedures, and the problem of accurate measurement including the absolute intensity calibration is an important research item in the soft X-ray region in many research fields. We have examined to study as a first step characteristics of a steady state hot electron plasma and to use it as an easily controllable reference source for promoting our study with the Gyrotron. By preparing a 2.45 GHz microwave with an output power below 3 kW in the cw mode, we have produced a hot electron plasma in a simple mirror field with a machine similar to the one reported in Ref. 11. A stable and reproducible plasma was easily obtained in various gas species. By measuring soft X-rays from this source, we have studied overall characteristics of the plasma to find optimum conditions to be used as a light source.

This paper reports on the experimental results obtained by this study. In Sec. 2 experimental procedures are described and in Sec. 3 experimental results are discussed separately for the cold and the hot component of the plasma. Emphasis is given on the determination of hot electron parameters by measuring the soft X-ray in various gas species.

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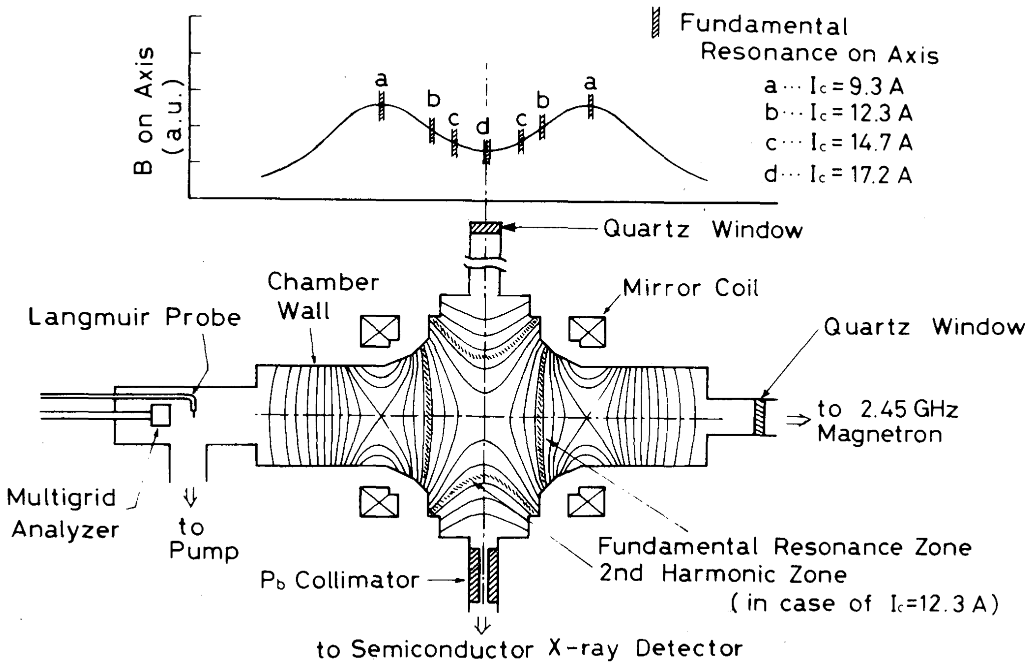

Fig. 1 Schematic diagram of experimental apparatus and diagnostic system.

2. Experimental Apparatus

Figure 1 shows schematic diagram of experimental apparatus and diagnostic system. The axial intensity distribution of the mirror magnetic field is also shown. The shaded marks indicate the fundamental resonance zone on the axis for various current I_c of the mirror coil which is the same one reported in Ref. 11. Experiments were carried out with the mirror ratio $MR = 2$. By the direct coupling of a rectangular waveguide to the vacuum chamber, microwave radiation with $f = 2.45$ GHz from a cw magnetron is fed to the chamber up to the power input of about 1 kW from the one end in the axial direction. Waveguide system between the chamber and the magnetron includes isolater, water load, directional coupler for detecting the reflected power and E-H tuner. The base pressure of the chamber reaches to about 4 $\times 10^{-5}$ Pa and the filling pressure p_0 ranges from 10^{-3} Pa to 10^{-1} Pa. An ECR plasma is produced in the vacuum chamber with a relatively low temperature bulk component due to a small input power below and around 1 kW. It includes, however, hot electron components due to the rapid heating of cold electrons by the ECR phenomenon. Soft X-ray radiation emitted by the existence of hot electrons is observed as Bremsstrahlung and recombination continuum and also as several characteristic line emissions. Constant flux contour of the magnetic field within the chamber is also shown in the figure with the fundamental and the 2nd harmonic resonance zones in case of $I_c = 12.3$ A, where the fundamental resonance zones lie at $z = \pm 10$ cm on the axis.

The soft X-ray from the plasma is measured with a Si (Li) semiconductor detector. The energy of the measured X-ray ranges from 1 keV up to 100 keV and in this experiment mainly the data in 1–10 keV are studied. A lead collimator is inserted to the evacuated SUS pipe connecting the plasma chamber and the detector as shown in the figure. It excludes scattered radiations from the chamber wall. By this collimation the detector is made to view only a part of the opposite quarz window surface through the plasma. Detected X-ray photons are analyzed with a PHA and their energy spectra are displayed after the data processing with a personal computer. A Langmuir probe is used to measure the electron temperature T_{ec} and its density n_{ec} of the bulk cold plasma. A multigrid analyzer is also used to determine the ion temperature T_i.

3. Experimental Results and Discussion

3.1 Cold plasma parameters

First we have measured parameters of the bulk cold plasma. They were studied mainly for Ar plasma. Changing the position of the Langmuir probe, axial distributions of n_{ec} and the floating potential V_f of the cold plasma were measured for various magnetic coil currents I_c as shown in **Fig. 2.** A low gas pressure of $p_0 = 6.7 \times 10^{-3}$ Pa corresponds to a pressure region where strong X-ray yield is obtained. When the probe is at the center of the plasma, overheating by hot electrons damages the probe at a high power input more than 200W. So that the measurement was limited in a relatively low power input of $p_\mu = 150$W. By changing I_c the fundamental resonance

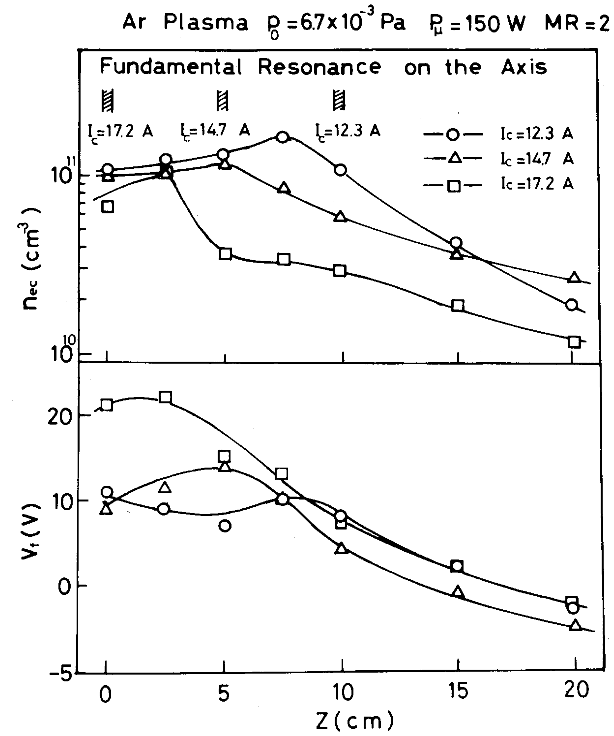

Fig. 2 Axial variation of cold plasma density n_{ec} and electron temperature T_{ec} on various coil currents I_c of the mirror magnetic field at P_μ = 150 W and p_0 = 6.7 × 10^{-3} Pa.

zone varies in the axial direction as described in Fig. 1 and also shown in this figure by the shaded mark. It should be remarked that for a fixed value of I_c the high electron density region lies within the two fundamental resonance zones in the axial direction and not within the two mirror throats at $z=\pm20$cm. This indicates that the cold electron distribution is strongly influenced by the hot electron population. Moreover at any coil currents, the position giving the peak value of n_{ec} lies near the resonance point and at the center n_{ec} shows a slight decrease. In the figure the maximum n_{ec} is about 1 × 10^{11} cm^{-3} and it is a little higher than the cut-off density n_c of the microwave which is 7.4×10^{10}cm^{-3}. The uncertainty in the probe measurement may be one reason of obtaining such a density. At the same time, however, in case of the axial injection of the wave, whistler wave can propagate without the cut-off density. It may make us obtain a higher value of n_{ec} than n_c as is observed in this experiment. At present it is not clear why the cold electron distribution has a dip at the center of the mirror. The floating potential distribution also shows a similar behaviour as that of n_{ec}. These results will reflect the close correlation between cold and hot electron populations in a simple mirror field. There is a posibility that the Langmuir probe might disturb the distribution, but its dimension is extremely small in comparison with the area of the resonance zone and the chamber volume. More detailed study will be performed on the clear reasons of obtaining these distributions and the result will be reported elsewhere.

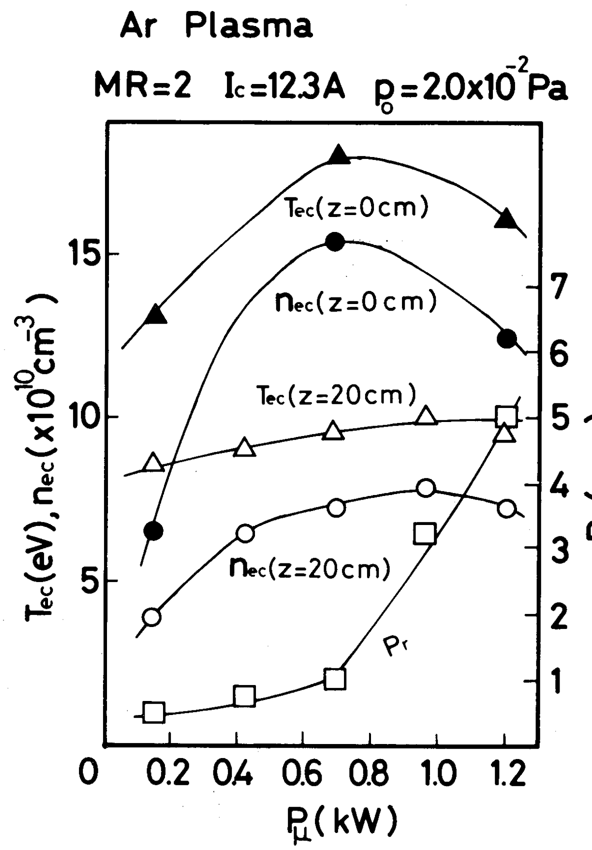

Fig. 3 Dependence of n_{ec} and T_{ec} on the input power P_μ of the microwave at p_0 = 2.0 × 10^{-3} Pa.

Cold plasma parameters at the center of the plasma were determined for various input powers of the microwave. In a high pressure, for example, of $p_0 \geqslant 2 \times 10^{-2}$ Pa, the probe could be used even at a high power of about 1 kW as the hot electron production rate was found to be so low. **Figure 3** shows the dependence of n_{ec} and T_{ec} with P_μ at p_0=2×10^{-2} Pa. The data at z=0 and 20cm are shown for comparison. Both the electron density n_{ec} and the temperature T_{ec} sharply grow with P_μ at the plasma center for $P_\mu \leqslant 0.7$ kW. But over this value of P_μ they are rather decreased. The differences of n_{ec} and T_{ec} at two positions show good correspondence with those obtained at p_0 = 6.7 × 10^{-3}Pa in Fig. 2. By increasing p_0 from 6.7 × 10^{-3} to 2 × 10^{-1}Pa, n_{ec} decreases to 60 to 70% at a low power input of P_μ = 150W. This indicates that P_μ is so low that it is impossible to increase n_{ec} even if p_0 is increased to a higher value. When p_μ is raised to 0.7 kW, however, n_{ec} is increased to a value of about 1.5 × 10^{11} cm^{-3} that is again higher than the cut-off density n_c. The additional power does not contribute to the creation of the cold plasma and the reflected power P_r begins to increase sharply at $P_\mu \geqslant 0.7$ kW, though its absolute value is found to be still so small. A further input of the microwave power mainly causes the increase in the hot electron density as will be discussed later. **Figure 4** shows dependence of n_{ec} and T_{ec} at z

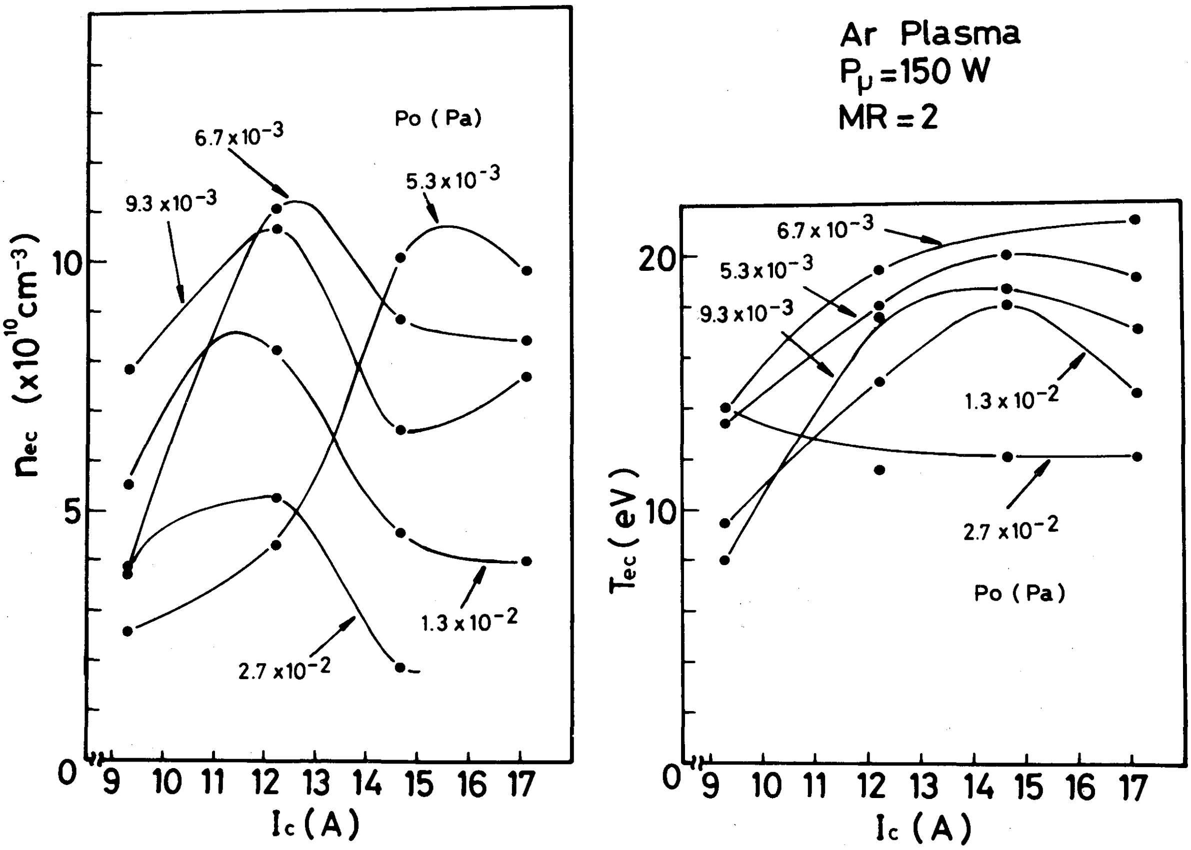

Fig. 4 Variation of n_{ec} and T_{ec} with the coil current I_c for various gas pressures at P_{μ} = 150 W and z = 0 cm.

= 0 and P_μ = 150 W on the magnetic coil current I_c for different gas pressures. In regard to n_{ec} it exhibits a peculiar dependence with I_c. At the lowest pressure of 5.3 $\times$ 10^{-3} Pa the maximum n_{ec} is obtained at $I_c \simeq 15$A. When P_0 is increased to 6.7 $\times$ 10^{-3} Pa, the peak position changes to a lower value of I_c with a little increase in n_{ec}, and a further increase of p_0 causes a little shift of the peak position accompanying a reduction in n_{ec}. A similar tendency is also observed in the soft X-ray measurement. They are essentially connected with the coupling problem of the microwave with the plasma and will also be discussed in the following sections. As for T_{ec}, there appears little tendency of peak variation and a gentle peak of T_{ec} is observed at a value of I_c around 12-15A. Typically the temperature decreases gradually with the gas pressure.

As for ion temperature T_i, the data obtained with the multigrid analyzer gave a low value of 1-3eV for all experimental conditions and the conclusion is that T_i is much smaller than T_e in the ECR plasma, which is the fact usually accepted well in a simple mirror field.

3.2 Soft X-ray measurement

A Si(Li) semiconductor detector was applied to measure soft X-ray spectrum including line emissions produced by the collisions of ions and neutral particles with hot electrons in the energy range of about 1 keV to 15 keV. We determined the hot electron temperature T_{eh} and its density n_{eh} from this data. X-rays from a plasma usually include low energy X-ray photons with a relatively high count rate and the resultant overcounting is likely to distort the spectrum. By collimating the X-ray pass as much as possible, the photon count rate is lowered to be sufficient for avoiding the spectral distortion. The correct collimation also contributes to observe only the X-ray from the plasma, not the scattered radiation from the wall. In our experiment each spectrum is obtained by the detection for a time interval between several seconds and several minutes.

In various rare gas plasmas strong low energy characteristic X-ray is also measured. Typical energy spectra from Ne, Ar and Kr plasma are shown in a logarithmic scale of intensity in **Fig. 5**. These spectra are, of course, calibrated ones in regard to the sensitivity of the detector on energy. In Ar plasma characteristic K_α line of 3 keV is clearly observed. Other lines also correspond to their characteristic spectra. The intensity ratio of line to continuum at the line center is about 20 to 40. In the figure it is clear that exponential slope of the continuous spectra enables us to determine T_{eh} and n_{eh}, assuming a Maxwellian electron distribution function in the energy range of 1 to 15 keV. In the work of Wieseman et al.[12], it is demonstrated that usually in an ECR plasma in a mirror magnetic field, electrons have not a Maxwellian distribution. They insist it will obey the e^{-nE} law, where n is integer and E is the electron energy. In their experiment $n = 1$ is found at least in Ar plasma. In our case we also checked this problem with the Langmuir probe, multi-grid analyzer and the X-ray detection over the wide energy range up to 100 keV using a Ge detector as well as the Si(Li) detector. In the bulk cold plasma we found a higher energy component with a temperature of 30–50 eV. In the X-ray measurement we could separate several components in the high energy tail of the distribution. So that certainly it seems that the whole energy distribution may not be a Maxwellian one. But at the same time we found that it did not obey the e^{-E} law as Wieseman suggested. We think this problem should be studied further with more detailed and sufficient data.

3.3 Parameters of hot electron component

Assuming a Maxwellian distribution for hot electrons we decided the hot electron temperature T_{eh}. From the estimation of absolute X-ray intensity we can determine the hot electron density n_{eh} when the plasma diameter is given by a fixed value. As stated earlier spectra of 0–15 keV range almost shows a Maxwellian distribution. In this sub-section Ar plasma is again studied. **Figure 6** shows dependence of the Ar Kα line intensity with the energy of 3 keV on the magnetic coil current in different gas pressures. The power input is 1.2 kW. We can find a similar dependence as in Fig. 3 though P_μ is remarkably different. At the gas pressure of 6.7×10^{-3} Pa the most intense line emission is observed at I_c = 16A. When p_0 is increased the peak shifts to a lower I_c accompanying a decrease in its intensity. Indeed the magnetic field strength giving a peak in the line emission shifts in correspondence with that of n_{ec} in Fig. 3. This result is also reflected in the variation of n_{eh} and T_{eh} as shown in **Fig. 7**. In the figure n_{eh} was decided assuming a plasma diameter of 20 cm which is a typical value reported in Ref. 11, where the same experimental apparatus was used in spite of the difference in the wave frequency. The maximum hot electron density obtained in this figure is $1.5 \times 10^{10}\,\text{cm}^{-3}$ and it is about 0.1 of the cold electron density. While the hot electron temperature ranges to 2–5 keV showing a similar peak variation with the gas pressure.

These results can be explained in the following way: When the gas pressure is low, for example $p_0 = 6.7 \times 10^{-3}$ Pa, a cold plasma with a high electron density larger than n_c is easily obtained at the plasma center even at P_μ = 150 W (c.f. Fig. 2). In this case the increase of P_μ to 1.2 kW produces sufficient hot electrons to emit soft

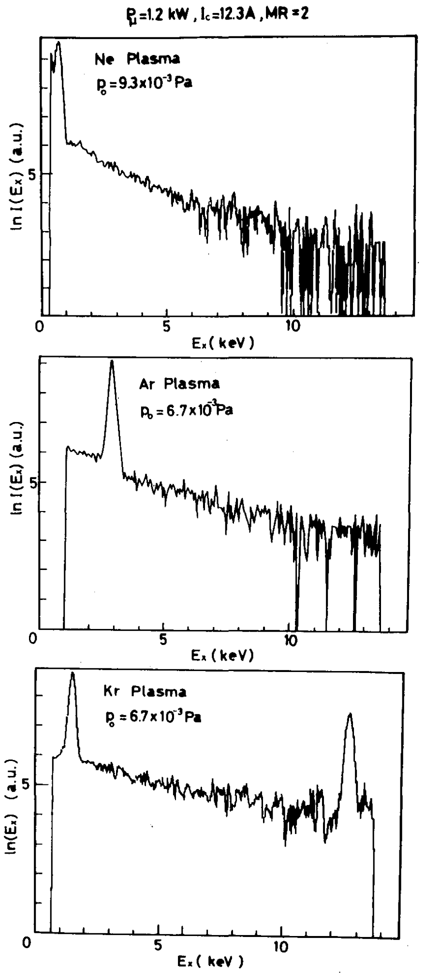

Fig. 5 Typical energy spectra of soft X-ray emitted from the plasma in various gas species.

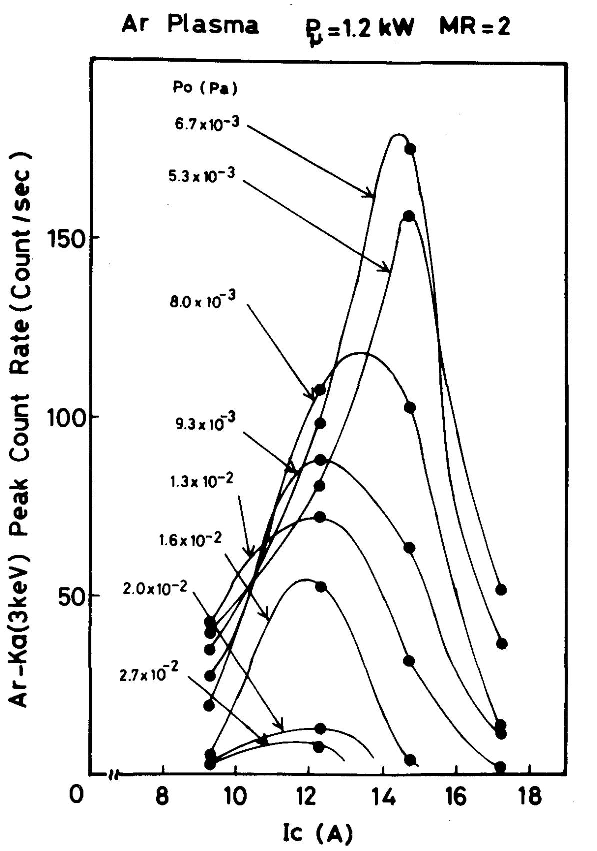

Fig. 6 Dependence of the intensity of Ar kα line (3 keV) on the coil current I_c for various gas pressures at P_μ=1.2kW.

X-rays remarkably. As the heating rate is usually higher in a stronger magnetic field, the largest n_{eh} can be obtained with the maximum T_{eh} at I_c = 14.7 A. When I_c is increased further, not only the resonance zone becomes distant from the wave input position but also it crosses the center of the plasma (c.f. Fig. 1), by which efficient heating of electrons by their bouncing motion between two resonance zones becomes very weak. This results in a decrease in n_{eh} and T_{eh} in case of I_c = 17.2 A. While when the gas pressure is as high as 2.0×10^{-2} Pa, n_{ec} at P_μ = 1.2 kW can be higher than that in case of $p_0 = 6.7 \times 10^{-3}$ Pa (c.f. Fig. 3). But a larger collisional process would bring a stronger decay of the injected wave energy in the axial direction before reaching to the resonance zone. To obtain hot electron component of the plasma the resonance zone must be made nearer to the wave input port by decreasing I_c. It in turn reduces the heating rate in comparison with the higher value of I_c. So that only lower n_{eh} with a lower T_{eh} can be obtained as shown in the figure. Indeed n_{eh} is smaller by one order even when p_0 is higher by about 3 as will be shown in Fig. 8. Thus we demonstrate that efficient coupling of the microwave to the plasma at the resonance zone in a strong magnetic field is a very important problem to obtain the hot electron component as much as possible or to make the bulk plasma to a hot electron temperature.

Next we have studied the power dependence of T_{eh} and n_{eh}. To make a comparison with n_{ec} and T_{ec} the data was taken in case of $p_0 = 2 \times 10^{-2}$ Pa and P_μ = 150 W, as the probe measurement was reliable enough in this case avoiding its overheating by hot electrons. The result is shown in Fig. 8. Compared to the cold component shown in Fig. 3, T_{eh} and n_{eh} increases steeply with the power until P_μ = 1.2 kW and it is clear that the additional power for $P_\mu \geqslant 0.7$ kW contributes mainly to the production of the hot electron component.

At P_μ = 150 W quite little X-ray radiation is detected as shown in Fig. 7 and n_{eh} is as small as below $1 \times 10^7 \mathrm{cm}^{-3}$. Even at P_μ = 1.2 kW, n_{eh} is obtained to be about $1 \times 10^9 \mathrm{cm}^{-3}$. In comparison with the data in case of $p_0 = 6.7 \times 10^{-3}$ Pa given in Fig. 7, it is very small but we may conclude that a high power input of the resonant microwave is also another important factor as well as its efficient coupling to the plasma at the resonance zone.

3.4 ECR plasma in various rare gases

Finally we have studied the difference of the plasma parameters in various rare gas species. He, Ne, Ar and Kr plasmas were produced and tested. **Figure 9** shows dependence of n_{eh} and T_{eh} on the gas pressure in different gas species. A similar dependence of n_{eh} is obtained for all species, but the pressure giving their peak values is higher in a gas with a smaller atomic number. Moreover a weaker decrease of n_{eh} with p_0 is clearly found in the lighter gas. These results can be considered to ocurr by the difference in the ionization potential E_i and/or ionization cross section. As E_i is larger in a lighter gas, a higher neutral particle density is necessary to obtain a similar hot electron density as is

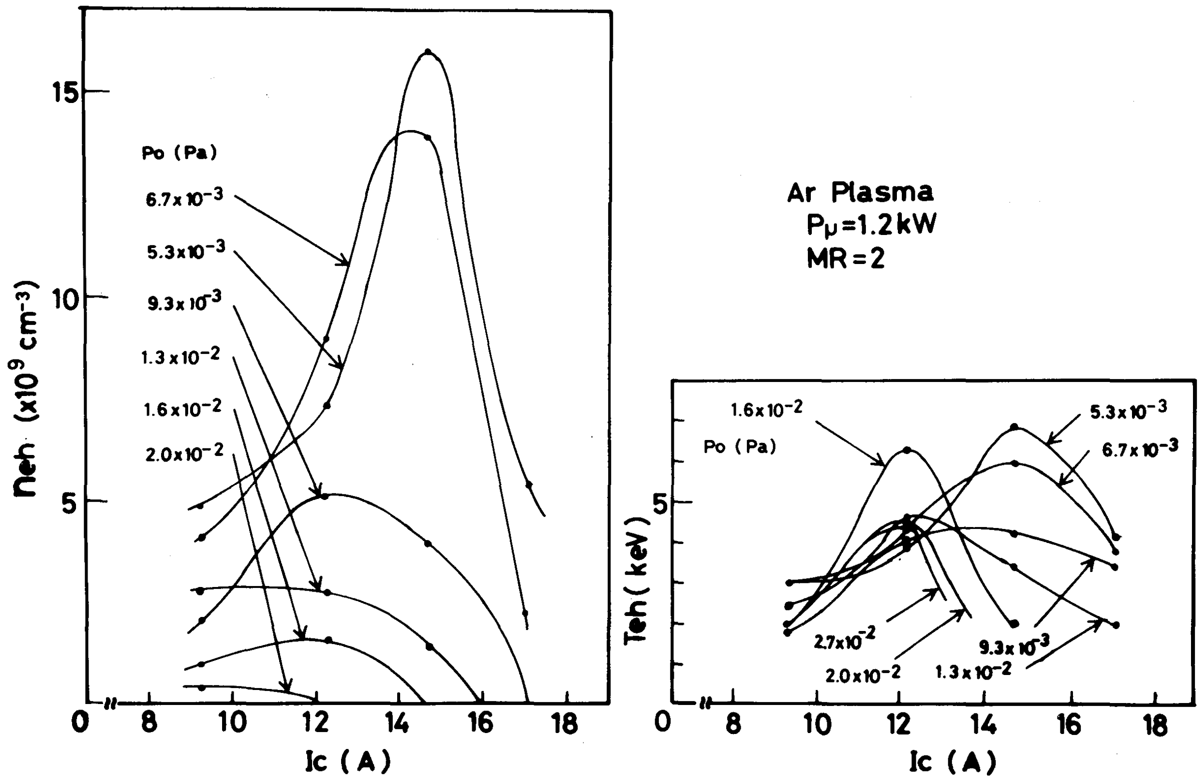

Fig. 7 Dependence of T_{eh} and n_{eh} on I_c for various gas pressures at P_μ = 1.2 kW.

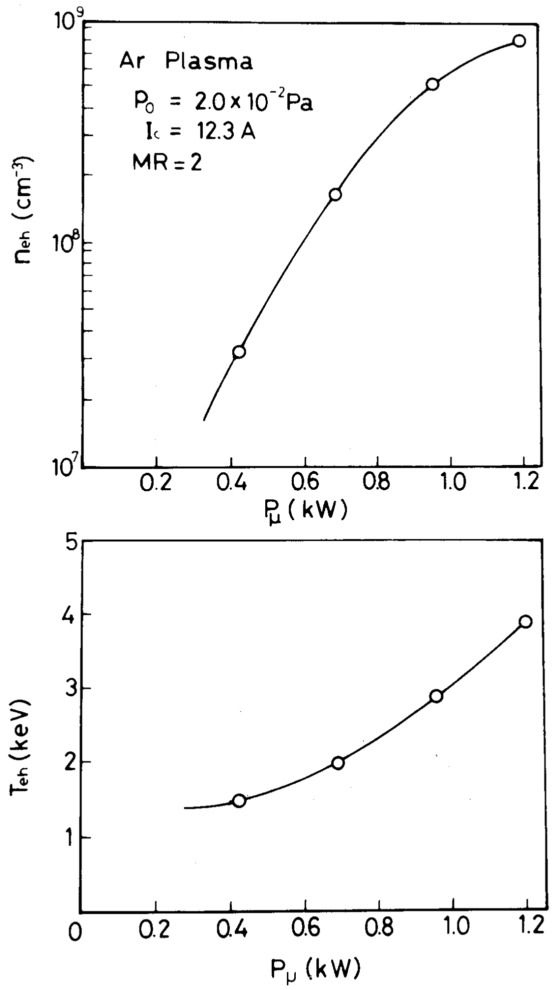

Fig. 8 Power dependence of T_{eh} and n_{eh} at p_0 = 2.0 × 10^{-1} Pa.

found in the right figure. It also shifts the pressure giving a peak T_{eh} to a higher one in He in comparison with in Ar, for example. While when the gas pressure is increased, hot electrons lose their energy lowering T_{eh} mainly by ionizing collision process. As the ionization cross section is smaller in a lighter gas, a comparatively weaker decrease of n_{eh} and T_{eh} with the gas pressure can be expected for He in contrast to Kr. Thus it make us suggest that hot electrons in a He plasma will decay more slowly in the afterglow phase. It will be examined in the experiment which will performed using a high power pulsed millimeter wave for the plasma production. The lower limit of the pressure in the production of the plasma comes from the fact that below this pressure even a cold plasma is not obtained stably. The upper limit of the pressure indicates a region above which the X-ray emission is not observed. Stable region of operation with soft X-ray emission is not wide in the gas pressure in a heavy gas.

4. Conclusion

In various rare gas species hot electron plasmas produced by an ECR discharge was studied experimentally in detail to know its overall characteristics. Parameters of hot and cold components of electrons were measured by changing various external parameters. The following results were clarified:

i) Cold plasma density n_{ec} reaches to a higher value of about 1 × 10^{11} cm^{-3} than the cut-off density of the

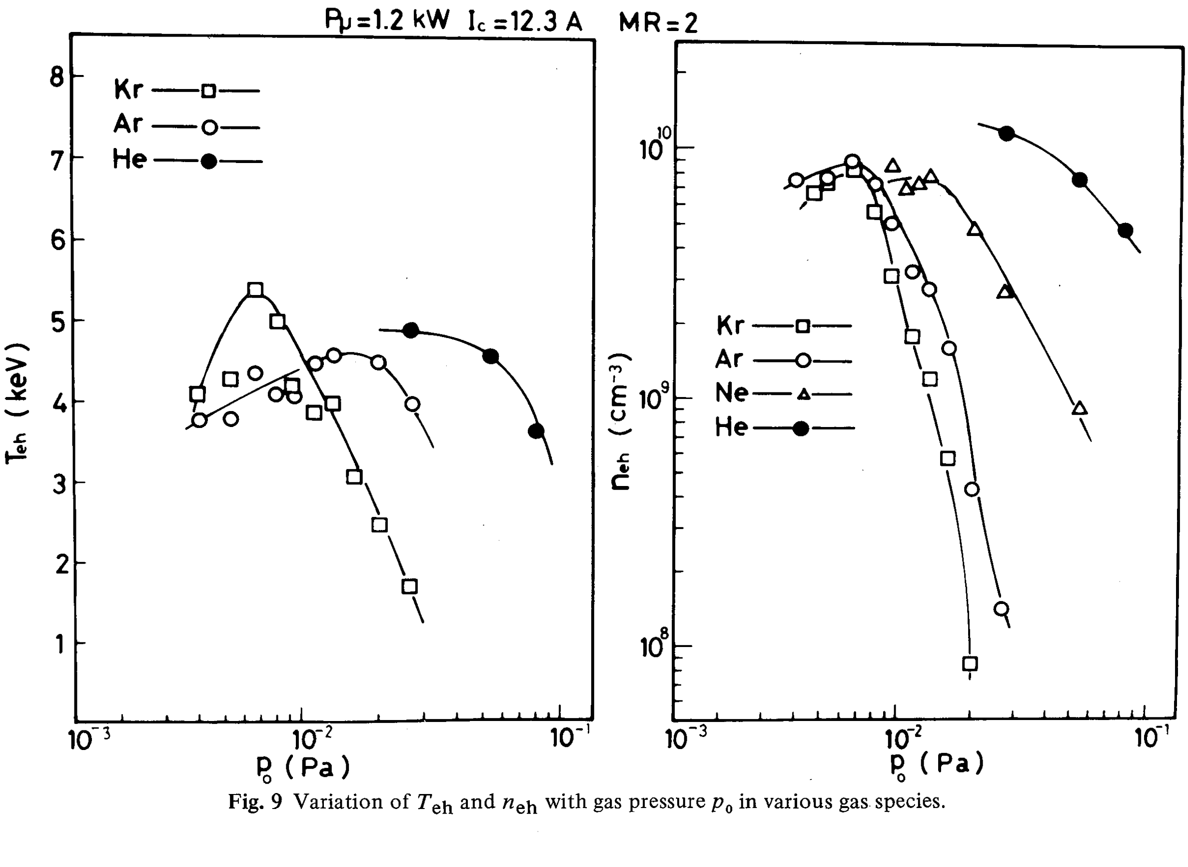

Fig. 9 Variation of T_{eh} and n_{eh} with gas pressure p_0 in various gas species.

incident wave, perhaps due to the axial launching by the whistler mode propagation.

ii) Cold electron temperature T_{ec} is typically 10–20 eV and ion temperature is always 1–3 eV quite smaller than T_{ec} as is usual in an ECR plasma in a mirror field.

iii) Production of hot electrons also affects the cold component showing a characteristic cold plasma distribution in the axial direction. The distribution has a sharp drop around the fundamental resonance zone.

iv) Efficient coupling of the wave to the plasma at the resonance zone in a strong magnetic field is very important for obtaining sufficient hot electrons with the emission of soft X-ray.

v) Also the high power input of the wave is found to be effective to make a plasma to a high temperature state of $T_{eh} \geqslant 1$ keV.

vi) Hot electron component has a density of about $1 \times 10^{10} cm^{-3}$ with a temperature of 2–4 keV at optimum conditions.

vii) Study of the plasma parameters in different gas species indicates that a difference is found in the value of the gas pressure at which the maximum hot electron production is obtained. The smaller the atomic number of the gas, the higher the pressure of an optimum condition. Also slower decrease of n_{eh} with p_0 is observed in a smaller atomic number. These two differences can be explained by the difference in the ionization potential and/or ionization cross section.

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