Structure of ECR Mirror Plasma†

Yoshiaki ARATA *, Shoji MIYAKE **, Hiroaki KISHIMOTO *, Yoshiaki AGAWA ******
and Nobuyuki ABE *****

Abstract

Structure of an ECR plasma in a simple mirror field were studied experimentally. From the measurement of cold plasma parameters it was found that the plasma was efficiently confined between the two resonance zones in the axial direction, when the gas pressure was low enough to produce sufficient hot electrons. While in the measurement of the radial distribution of soft X-ray emission, it was verified that also the 2nd harmonic resonance zones contributed to the production of hot electrons as well as the fundamental ones.

KEY WORDS: (ECR Plasma) (Mirror Plasma) (Soft X-ray) (Hot Electron) (2nd Harmonic Heating)

1. Introduction

In the study[1] of soft X-ray emission from an ECR plasma in a simple mirror field, optimum operating conditions were made clear to obtain efficiently a stable hot electron component at a fixed magnetic field configuration. The plasma was produced by an axially injected microwave radiation of $f = 2.45$ GHz in various gas species. The X-ray emission was measured by a Si (Li) semiconductor detector in the energy range of 1 – 15 keV. Typically Ar plasma parameters were evaluated and it was demonstrated that the plasma production and heating was strongly affected by the axial flow of the plasma where the incident wave was attenuated before reaching to the fundamental resonance zone. We have performed further experiments to check this problem in more detail and also to know the effect of the second harmonic resonance heating which is known to form a hot electron ring in the central region of a mirror plasma. To know the spatial distribution of hot electrons, we have applied a gas-flow proportional counter and detected low energy soft X-ray of 0.1 – 2 keV in the radial direction. In this paper is reported experimental results on the structure of an ECR plasma reduced from the measurement of the distribution of soft X-ray and/or cold plasma parameters.

2. Experimental Procedure

The experimental apparatus used is the same with the one reported in Ref. 1. The magnetic coils, however, was changed to the one made from normal conductors which kept the same magnetic field configuration. **Figure 1** shows scheme of the energy dispersive soft X-ray detection system. The gas-flow proportional counter (Model 04, Manson) is traversed vertically with the axis of rotation at the position of the bellow. With the use of a Pb-collimator the detector views a vertical plasma dimension of about 5 mm at each position. The ionizing gas of the detector is the mixture of 90%Ar and 10%CH_4 (P-10). In this gas mixture photons in the energy range from 0.1 to 2.5 keV can be detected with a considerable sensitivity. As for the data in the range from 1 to 15 keV obtainable by the Si (Li) detector, it was reported in the previous paper and some additional informations are given again in this report. To know the axial variation of the cold plasma parameters we have used a Langmuir probe.

3. Results and discussion

3.1 Axial structure

A Langumuir probe was moved to measure the axial variation of the cold plasma parameters. **Figure 2** shows distributions of the electron density of the cold plasma component for various values of Ar gas pressure and input microwave power. In the lower right of the figure is also drawn the fundamental and 2nd harmonic resonance zone within the vacuum chamber at a coil current I_c of 417A and a mirror ratio $MR = 2$, where the distance between the two coils is set to be 37.5 cm. The fundamental

† Received on Nov. 6, 1986
* Professor
** Associate Professor
*** Graduate Student
**** ULVAC Corporation, Chigasaki, Kanagawa
***** Research Instructor

Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

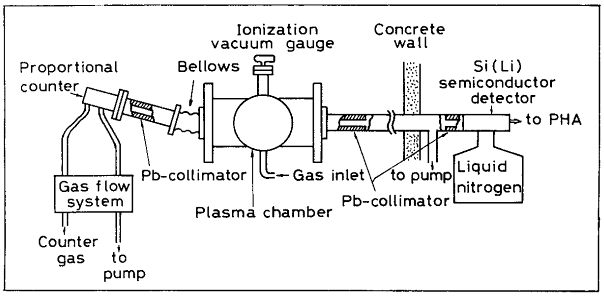

Fig. 1 Scheme of the energy-dispersive soft X-ray detection system.

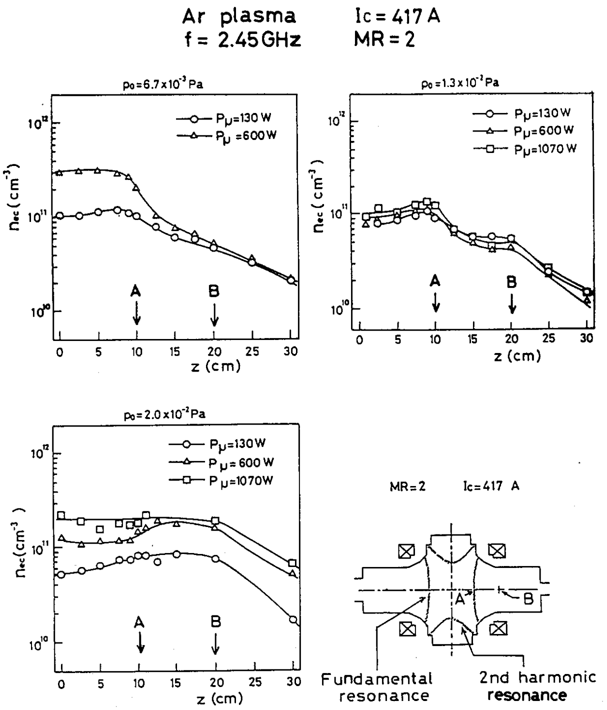

Fig. 2 Axial distribution of n_{ec} for various values of Ar gas pressure and input microwave power.

resonance point on the axis are marked by A and the position of the mirror throat is designated by B. We can clearly find that the electron distribution shows a marked variation with the gas pressure. In the case of $p_0 = 6.7 \times 10^{-3}$ Pa, the cold electron density n_{ec} shows a sharp drop near the fundamental resonance point A positioned at $z = \pm 10$ cm. While at $p_0 = 1.3 \times 10^{-2}$ Pa it makes a remarkable change also near the point B. When p_0 is increased further to a value of 2.0×10^{-2} Pa, the electron density decreases only from B in the axial direction. These results indicate that when the gas pressure is low enough electrons are effectively heated and confined between the two resonance zones in the axial direction, and the reflection of particles at the mirror throat does not play an important role for the confinement. Meanwhile at a high pressure only the confinement effect at the mirror throat is observed and the resonance zone mainly serves to produce warm and/or cold electrons with little effect of electron reflection through the resonant increase of its magnetic moment. In other words the plasma axially extends by the increase of the gas pressure, and it will surely affect the wave propagation in the axial direction. In the previous paper it was demonstrated that the decay of the input microwave before reaching to the resonance zone in the axial direction would make the lowering of the efficiency of the production and heating of the plasma. The result in Fig. 1 indirectly certifies this interpretation, although the measurement of the wave damping has not been performed yet.

As for the confinement effect of the plasma between the two resonance zones in the axial direction, we have further checked it by varying the resonance position and the mirror ratio. We also made an experiment in the cusp magnetic field. When the coil current was varied, the point A axially moved and a sharp drop of n_{ec} was observed around this point for each coil current as reported in Ref. 1. **Figure 3** shows the axial variation of n_{ec} and cold electron temperature T_{ec} for $MR = 2$ and 4. In the case of $MR = 4$ the distance between the two coils was varied to 53.5 cm and the point A was changed to $z = \pm 20$ cm at

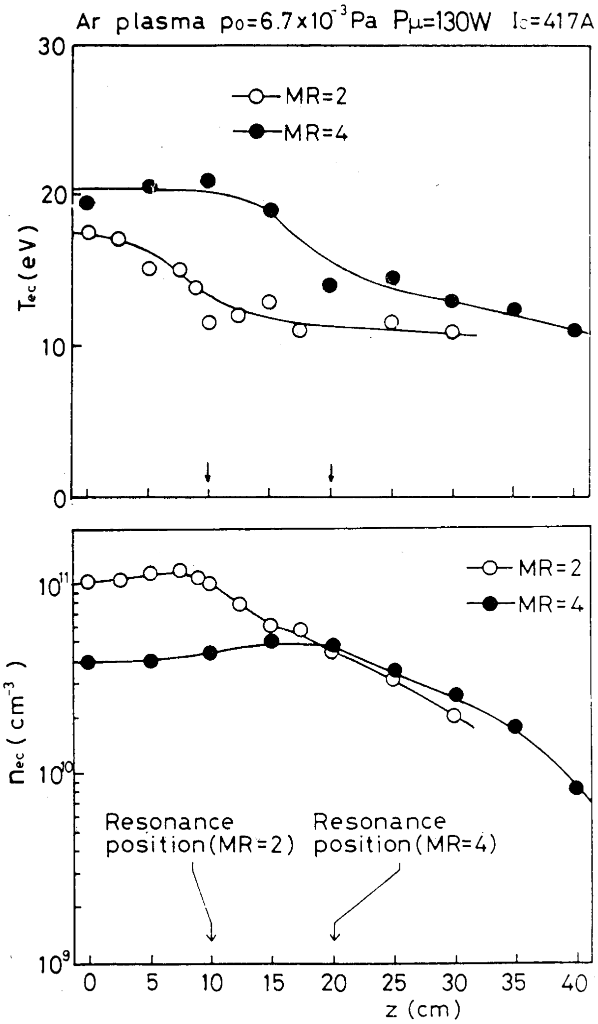

Fig. 3 Axial distribution of n_{ec} and T_{ec} for two values of the mirror ratio $MR = 2$ and 4.

$I_c = 417$A. The cold electron density again shows a steep decrease after the resonance point in both cases. The electron temperature also indicates a similar variation. These results clearly inform again that the multiple reflection of electrons between the two resonance zones contributes to the plasma confinement by the increase of their magnetic movement via the resonant energy gain from the microwave. In **Figure 4** is shown the axial distribution of n_{ec} and T_{ec} in a mirror and a cusp magnetic field. The coil current was adjusted to keep the resonance point A at the same position in both configurations. We can see that in the mirror field n_{ec} and T_{ec} are remarkably higher between the center and the resonance point. While in the cusp field there appears quite little variation of n_{ec} and T_{ec} in the axial direction. Only a gradual decrease of n_{ec} is found from the position B of the maximum magnetic field. Moreover we remark that in the cusp field we have observed almost no emission of soft X-ray with an energy over 1 keV in the measurement with the Si (Li) detector. This result indicates that in the mirror field the ECR effect at the resonance point serves to confine and heat the plasma, while in the cusp field it mainly acts only to ionize neutral particles with less efficiency of heating.

In the production and heating of a plasma using the ECR effect in a simple mirror field, usually cold and hot electrons are said to coexist over a definite range of the gas pressure. But the definition of the temperature

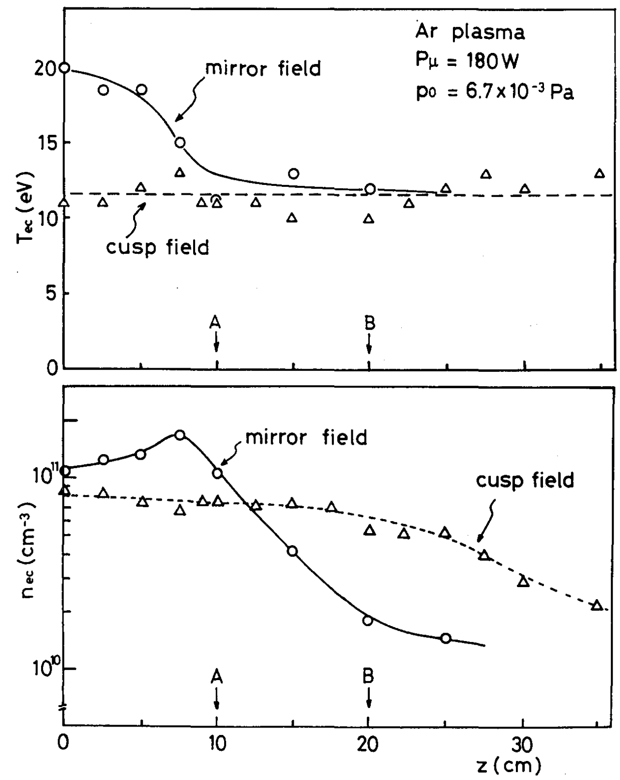

Fig. 4 Axial distribution of n_{ec} and T_{ec} in a mirror and a cusp magnetic field.

by which cold and hot components are distinguished has not been clarified at all. Each researcher has made his own designation. Usually cold electron parameters are determined from the Langmuir probe measurement by which T_{ec} has a value below 100 eV. While hot electron parameters has been typically determined using a pure Ge semiconductor detector and/or a NaI scintillation counter. So that the hot electron temperature T_{eh} ranges over several ten or several hundred keV, and there has been little study on the energy spectrum of electrons in the intermediate range of 0.1 – 10keV. In the previous paper we have reported for the first the data in the range of 1.0 – 15 keV using a Si (Li) semiconductor detector, and those electrons were designated to be hot component. Electrons with higher energies were also measured using a Ge detector but their numbers were so low that we omitted them in considering the plasma properties. As for the data in the range of 0.1 – 2 keV the result is reported in the present study, and we also designate them to be hot electrons.

Anyway there is a close correlation in the production of cold and hot electron components. **Figure 5** shows the dependence of cold electron density and Ar-K_α line emission with an energy of 2.96 keV on the coil current of the mirror field at MR = 2. This dependence was already analyzed in Ref. 1 in close correlation with the axial elongation of the plasma with the gas pressure. We can see that the cold electron density and the high energy photon intensity show a similar variation with gas pressure and coil current. When the gas pressure is higher than 1×10^{-2}Pa or so, however, hot electrons almost disappear and only cold electrons are produced efficiently up to the gas pressure of about 1×10^{-1}Pa. This feature is shown in **Fig. 6**. The hot electron density n_{eh} determined from the data in the range of 1 – 15 keV by the Si (Li) detector is appreciable only when $p_0 < 1 \times 10^{-2}$Pa at $I_c = 333$A, even though the input power is high enough. While variation of n_{ec} determined from the probe measurement is divided into two modes.

In a discharge plasma it is generally known that at a fixed input power the ionization rate is increased with the gas pressure. It has, however, a maximum value at a certain pressure, since the electron temperature is lowered with the pressure in contrast to the increase of the neutral particle density. The optimum pressure is usually obtained around 1×10^{-1}Pa. Meanwhile in the case of an ECR discharge resonant interaction of the wave with electrons brings out production of hot components with an energy higher than 100 eV in a low pressure region. This effect is manifested more in a mirror field, since bounce motion of electrons between the two mirrors results in repeated heating at each passage of the resonance zone, an example of which we already found in Fig. 4. In such a case the

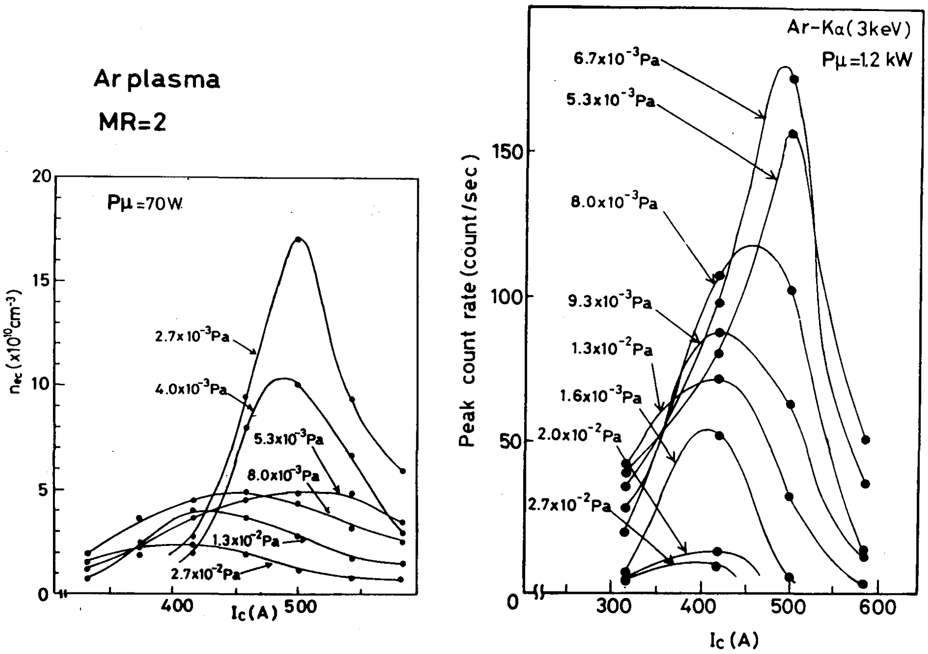

Fig. 5 Dependence of cold electron density and Ar-K_α line intensity on the coil current.

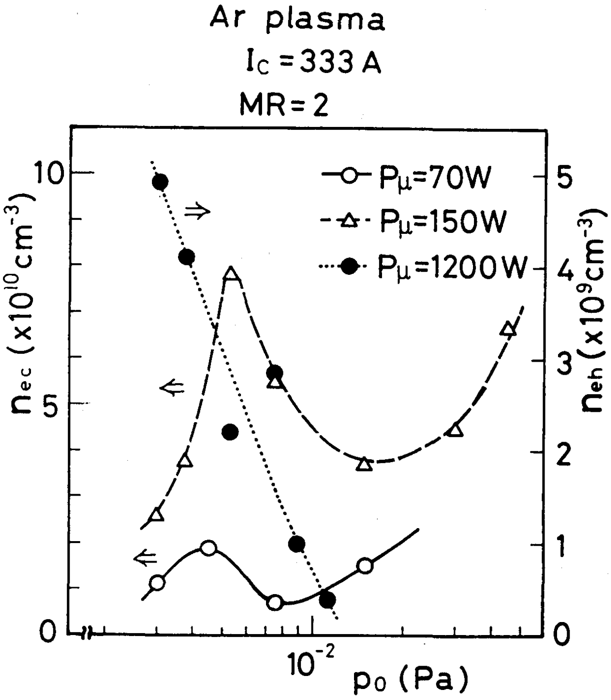

Fig. 6 Variation of n_{ec} and n_{eh} with gas pressure.

secondary ionization of the residual neutral gas by the hot electrons trapped in the mirror for a long time will dominate over the ionization by the non-trapped cold electrons.

Thus the increase of n_{ec} at $p_0 \geqslant 1 \times 10^{-2}$ Pa can be attributed to the first process of electron production without hot component. While the appearance of a peak in n_{ec} in the region of $p_0 < 1 \times 10^{-2}$ Pa, where hot electrons are efficiently obtained, is considered to be due to the second process. The enhancement of this peak is large in a high power input, and it is easily understood by the fact that hot electron production is a strong function of the power input as we have reported in Ref. 1. Thus it is demonstrated that cold electrons in Fig. 5 originates almost from the secondary ionization process by hot electrons. This property was also confirmed in the case of MR = 4, and we can consider that the axial distribution of hot electrons is similar to that of cold ones such as shown in Figs. 2 – 4 in the pressure region of $p_0 \leqslant 2 \times 10^{-2}$ Pa.

3.2 Radial structure

Next measurement has been performed on the radial distribution of hot electron component using a gas-flow proportional counter. **Figure 7** shows a typical example of the soft X-ray spectra in the energy range of 0.1 – 1.5 keV in Ne and O_2 plasmas. Characteristic K_α lines are clearly observed on the background continuum spectra. By the measurement of these X-rays at each position in the radial direction the distribution of hot electrons in the central region of the plasma column is easily obtained. **Figure 8** shows lateral distributions of photon emission with an energy of 170 eV in the Ar plasma at a microwave power P_i = 1.07 kW. Data in different gas pressures and coil currents are given without Abel inversion and we find a peculiar variation of the distribution.

First the maximum count rate is decreased with the gas pressure as a whole. In (a) of the figure, however, the most intense emission is obtained at a high coil current I_c = 583A when p_0 = 4.0 × 10^{-3}Pa. While at p_0 = 6.7 × 10^{-3}Pa it is found for I_c = 417A in (b), and in the case of p_0 = 2.0 × 10^{-2}Pa it is obtained at I_c = 333A, as we

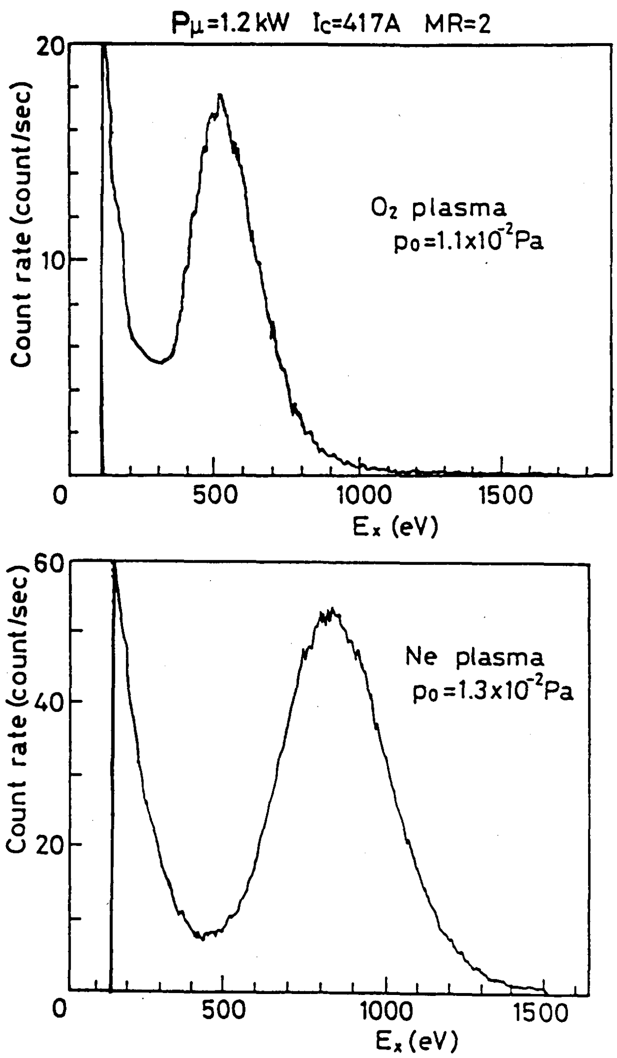

Fig. 7 Typical soft X-ray spectra in the energy range of 0.1 – 1.5 keV in Ne and O_2 plasma.

can see in (d). Indeed this tendency is the same with the one reported and discussed in the previous paper in the analysis of n_{eh} and T_{eh} evaluated from the data by the Si (Li) detector.

Next in each distribution, especially in (b) and (c), we remark that there appears a hump at a certain lateral point and it moves with the coil current. In the case of $MR = 2$ the 2nd harmonic resonance zone always lies on the off-axis area in the central part of the plasma when the coil current $I_c > 300$A. At $I_c = 417$A, for instance, the 2nd harmonic point in the radial direction at $z = 0$ cm is given at $r = \pm 10$ cm. We can clearly find the hump around this position. When I_c is 583A, the point moves to $r = \pm 15$ cm and the hump is again observed around this position. As the wavelength of the incident microwave is over 10 cm, the wave will be distributed almost uniformly within the vacuum chamber. So that we may consider that the central peak of the soft X-ray emission is brought by the heating in the fundamental resonance zone and the off-axial peak by the 2nd harmonic heating.

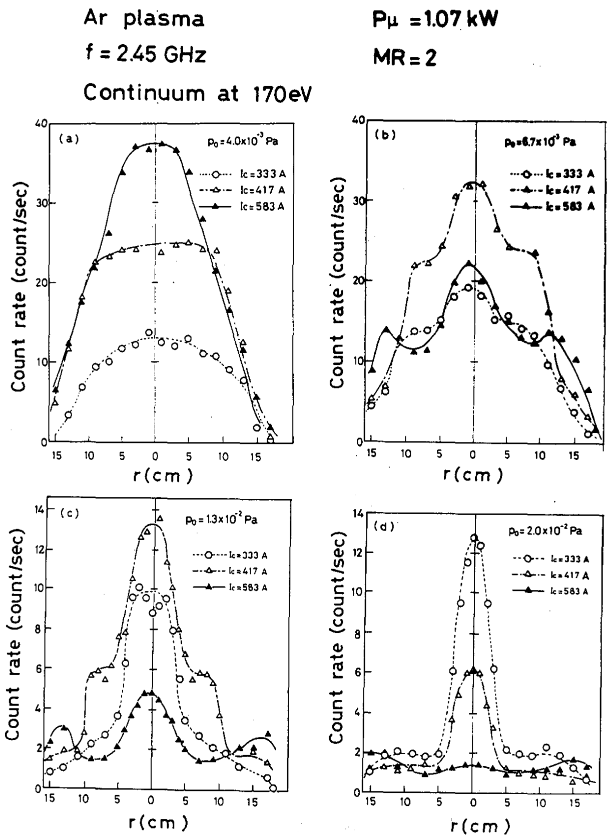

Fig. 8 Lateral distribution of 170 eV photon emission for various values of gas pressure and input power.

We have performed the same measurement at $MR = 4$. The result is shown in **Figure 9**, where the 1st and the 2nd harmonic resonance zones for MR = 2 and 4 are drawn in the upper part at a fixed value of I_c = 417A. Indeed at MR = 4 there appears no hump in the intensity distribution in the radial direction, since the 2nd harmonic zones are not located on the midplane of the plasma column as far as $I_c < 620$A.

The 2nd harmonic heating was also checked in other gas species. **Figure 10** shows an example of the lateral distribution of the soft X-ray emission in Ne plasma. The photon energy is again selected to be 170 eV. We can clearly find a similar property in each distribution with Ar plasma. The same tendency was also found in O_2 plasma.

4. Conclusion

From the measurement of axial and radial distributions of the plasma parameters structure of an ECR mirror plasma in Ar gas was made clear. From the axial structure of the cold electron density and its temperature, it was verified that in a low pressure region below 1 $\times 10^{-2}$Pa two resonance zones in the axial direction served to confine the plasma with repeated heating of electrons by their bounce motion. Production of cold electrons in this pressure range showed a peak at a certain

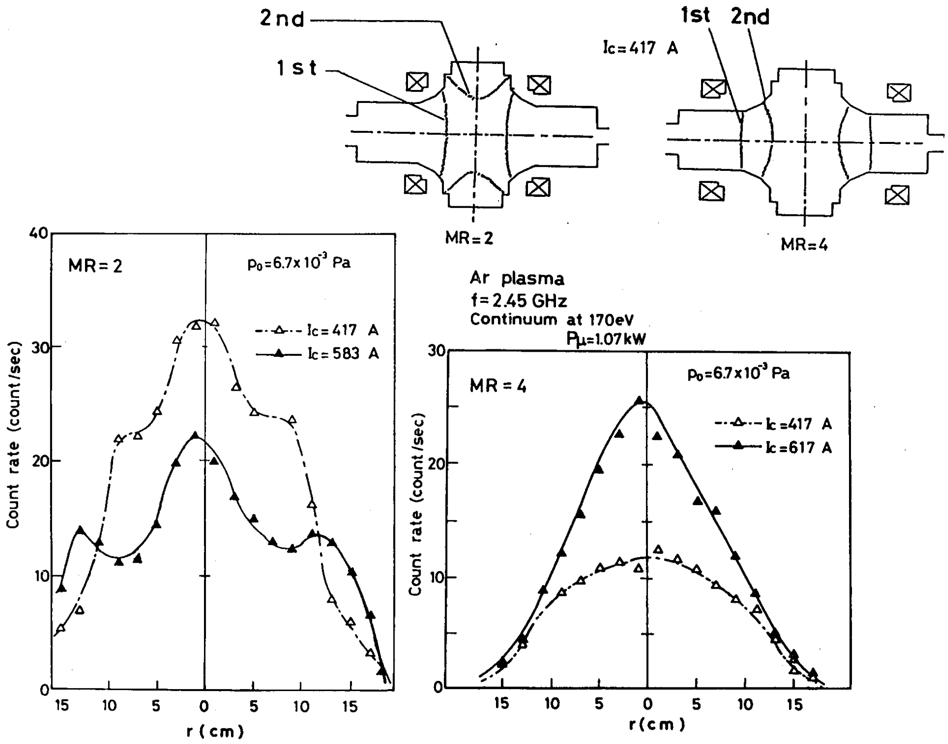

Fig. 9 Lateral distribution of 170 eV photon emission for MR = 2 and 4.

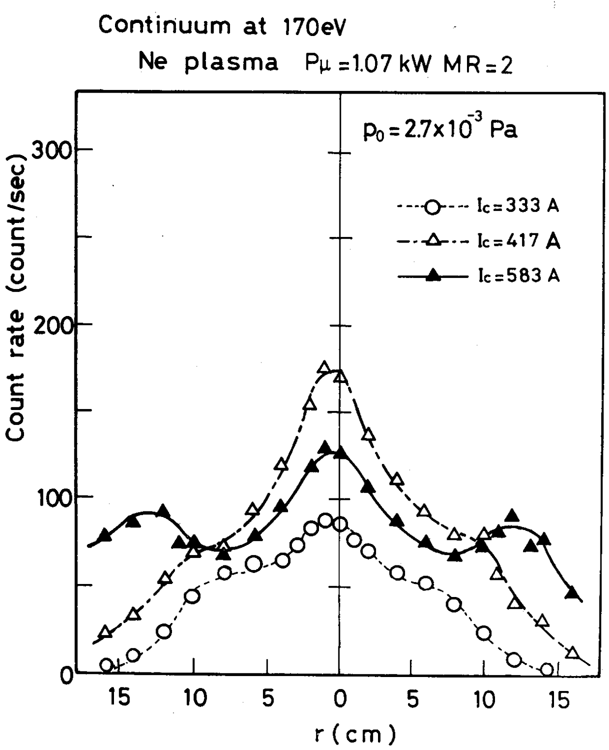

Fig. 10 Lateral distribution of 170 eV photon emission from Ne plasma.

pressure and was attributed to the secondary ionization process by the hot electrons confined for a long time in the mirror field with an energy higher than 0.1 keV. When the gas pressure was higher than 1×10^{-2} Pa, mainly cold electrons were obtained with little emission of soft X-ray. The cold electron density increased with the pressure until about 1×10^{-1} Pa. In this region, however, electrons were produced through usual collisional ionization process with little effect of confinement in the mirror field.

In the measurement of soft X-ray in the energy range of 0.1 – 1.5 keV, we have used a gas-flow proportional counter. We could successfully obtain its radial distribution over the wide range of the gas pressure, coil current and the input power in various gas species. The distributions showed peculiar variations by the change of the pressure and the coil current. It was found that the 2nd harmonic heating effect was remarkably important as well as the fundamental one, and gave a strong influence to the radial structure of the plasma.

By these measurements we conclude that how to design the positioning of the 1st and the 2nd harmonic resonance zones in the vacuum chamber will be the most important factor to govern the ECR plasma properties in a simple mirror field, and it is also a very important problem in the application of an ECR plasma for processing various new materials.

Acknowledgement

The authors would like to thank to Prof. Y. Kawai for his critical comments to this work.

References

1) Y. Arata, S. Miyake, N. Abe, H. Kishimoto and Y. Agawa: Trans. of JWRI **14** (1985) 47.