ECR Plasma in a High Power Millimeter-Wave Beam (Report II)†

– Time Variation of Electron Density –

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Abstract

Using a quasi-steady high power 60 GHz Gyrotron a high density and high temperature Ar plasma is produced in a simple mirror field. Time variation of the electron density n_e is studied in detail for various external parameters. The filling gas pressure before discharge is set around 1×10^{-1} Pa. Complicated variation of the line density with time is observed. Strong punping effect of the neutral gas by the plasma causes a rapid reduction of the gas pressure and a decrease of n_e after the fast build-up process of the plasma during the high power millimeter wave input. The line density reaches to a nearly constant value at t=20–30ms and an almost fully ionized plasma is sustained with n_e=4–5×10^{12}cm^{-3}. The efficient electron heating is also observed in this stage accompanying a rapid hot electron production. In the after-glow phase hot electrons continue to ionize the background neutral gas showing a long decay time of 30–50ms. The importance of a high power input to the plasma is verified to obtain a high density and high temperature state of the plasma.

KEY WORDS: (ECR Plasma) (Millimeter Wave) (Gyrotron) (Electron Density) (Microwave Interferometer) (Diamagnetic Flux) (Hot Electron)

1. Introduction

In Report I[1] the program plan on the efficient usage of a high power 60 GHz Gyrotron to a high temperature plasma production was described with some preliminary experimental results. A favorable specification of the Gyrotron used was also demonstrated in obtaining a dense and hot ECR plasma. The wave frequency of 60 GHz corresponds to the maximum electron density n_e of 4.5 × 10^{13} cm^{-3} to be obtainable in case of perpendicular launch of the wave to the magnetic field. The high output of more than 100 kW of the Gyrotron in a quasi-steady state will enable us obtain a high temperature plasma with the electron temperature T_e of 0.1–10 keV.

Application of this kind of a plasma would be very efficient for the development of a high intensity soft X-ray source and a high current simply or multiply charged ion sources. Of course, it will also be a very useful and promising source for plasma processing of various materials.

According to the program plan we have extensively performed series of experiments and obtained various interesting results. As the first report of these results, the time variation of electron density in Ar plasma are studied in this paper by changing various external parameters to make clear the plasma production process in detail. A rapid plasma production is verified with a high density reaching to the cut-off of the incident millimeter wave. Strong pumping effect of the neutral gas by the plasma is also observed after the build-up stage of the electron density and efficient electron heating is clearified in the quasi-steady state regime. It is made clear that the high frequency and high output of the Gyrotron is very efficient and reliable for obtaining a dense and hot ECR plasma.

† Received on Nov. 11, 1985

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

2. Experimental Procedures

Experimental apparatus and diagnostic system are the same as the ones described in Report I, which is shown in Fig. 1. To measure the electron density integrated over the chord of the plasma column (the line density), two interferometers were used. They are 8 mm and 4 mm microwave interferometers, which were set at the same observation port to see the same plasma area. Diamagnetic loops and a photodiode detector are also used to compare the variation of n_e with other parameters. As the pressure variation was found to be very large during the millimeter wave input, we used a nude gauge to obtain a correct time variation of the pressure. In this case electron or ion flow from the plasma is apt to be collected to the gauge, which will make a large error in the pressure measurement. So that by inserting a grid in front of the gauge we excluded the inflow of charged particles from the plasma to the gauge, by which a strong decrease in pressure was correctly evaluated.

The pressure range of Ar gas used in the experiment is around 1×10^{-1} Pa and the input power P_μ to the plasma ranges to 5–70 kW with the pulse duration of 100 ms. In the experiment also the mirror ratio MR is varied from 2 to 4.6 to know the difference in the plasma parameters. In the lower part of Fig. 1 magnetic line of force and flux density of the mirror field are shown for two mirror ratios of 2 and 4 at the coil current I_c of 300 A. In case of MR = 2 two fundamental electron cyclotron resonance zones lie at $z \simeq \pm 10$ cm in the axial direction, while in case of

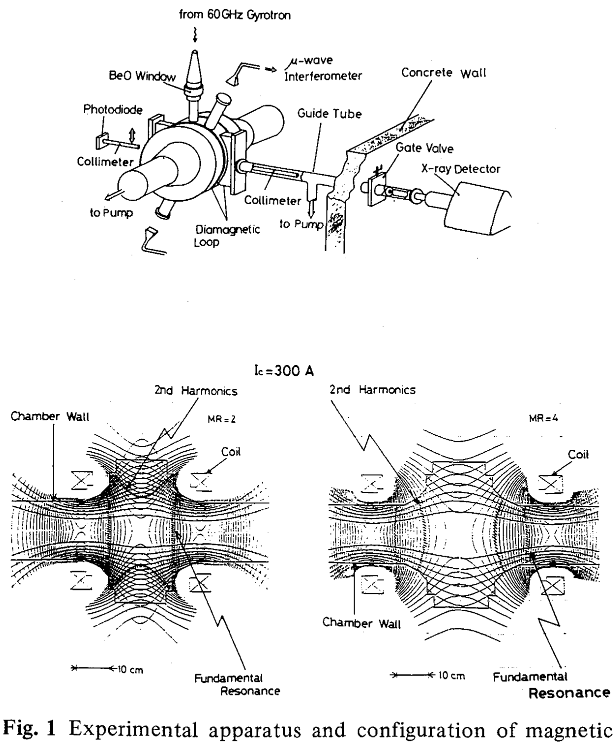

Fig. 1 Experimental apparatus and configuration of magnetic mirror field.

$MR = 4$ it is at $z \simeq \pm 20$ cm far from the wave launching zone of z = 0 cm. Moreover when MR = 2 the second harmonic zones lie within the wave launching section in the central part of the chamber. These two factors will give a remarkable difference in the production and heating of the plasma.

As for X-ray measurement we give no result in this report and the detection is performed only for the qualitative estimation of the heating process and the check of the reproducibility of the plasma shot to shot.

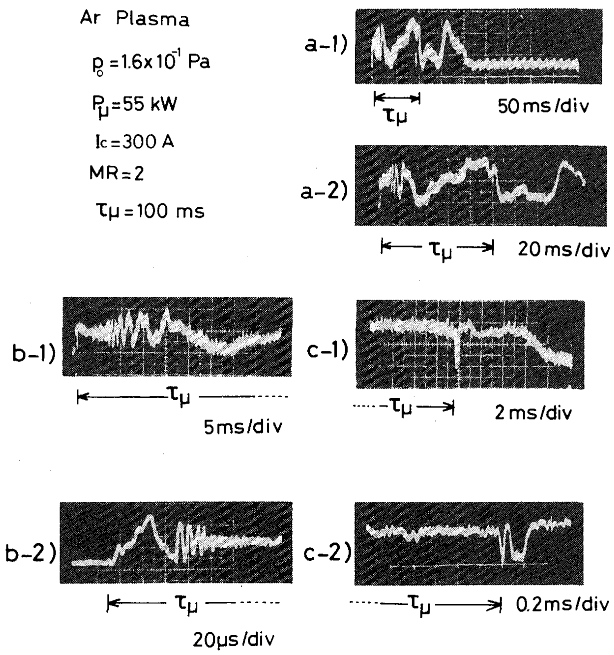

Fig. 2 Typical fringe patterns by 8 mm interferometer.

3. Results and Discussion

Figure 2 shows typical fringe patterns of 8 mm microwave interferometer used for a plasma at p_0=1.6$\times$10^{-1}Pa and P_μ= 50 kW. In the figure a-1) and a-2) show the total variation of the fringe shift recorded in two time scales. In these traces it should be noted that many fringes appear during the power input and a remarkable variation of the fringe still continues even after the time τ_μ of the millimeter wave launch. Also a very fast variation of the electron density is observed in the start-up phase of the discharge. To know in more detail these variations the time scale of the observation was shortened both in the start-up phase and in the afterglow. The results are shown in b-1, 2) and c-1, 2). In b-2) the start of the plasma production is clearly observed by the phase shift of the fringe just after the power input. At about 100 μs after the start of the discharge, the pattern shows no variation indicating the cut-off of the 8 mm microwave by the plasma. The build-up time of the plasma density is evaluated from this data to be about 25 μs. At the cut-off condition of the 8 mm microwave $n_e = 1.75 \times 10^{13}\,\mathrm{cm}^{-3}$ and it seems that n_e is still growing up after $t = 100\ \mu$s. While as we can see in b-1), after $t \simeq 5$ ms the fringe shift appears again showing a decrease of n_e with time. In the afterglow phase of the plasma, n_e sharply drops to a very low value just after the shut-off of the power input as c-1) clearly indicates. But n_e again begins to increase at about 100 μs after the shut-off and shows a very long decay time. These structures indicate a rather complicated variation of n_e with time during and after the millimeter wave input from the Gyrotron.

To check the validity of this measurement we applied a 4 mm microwave interferometer to the same plasma and compared their results. **Figure 3** shows typical fringe patterns by two interferometers and the time variation of the line density n_eL obtained by these detectors. In the figure L corresponds to a plasma diameter which will be estimated from other data. Each fringe pattern gave a very good reproducibility shot to shot. As we can see in the lower part of the figure two interferometers give a coincidental result on the time variation of n_eL. Thus we can believe the correct measurement of n_eL by these microwave interferometers with a high accuracy and good reproducibility.

We can see in the figure that n_eL strongly decreases as stated earlier in the time interval of $t \leqslant 20$ ms and it reaches to a nearly constant value at $t \geqslant 30$ ms. While

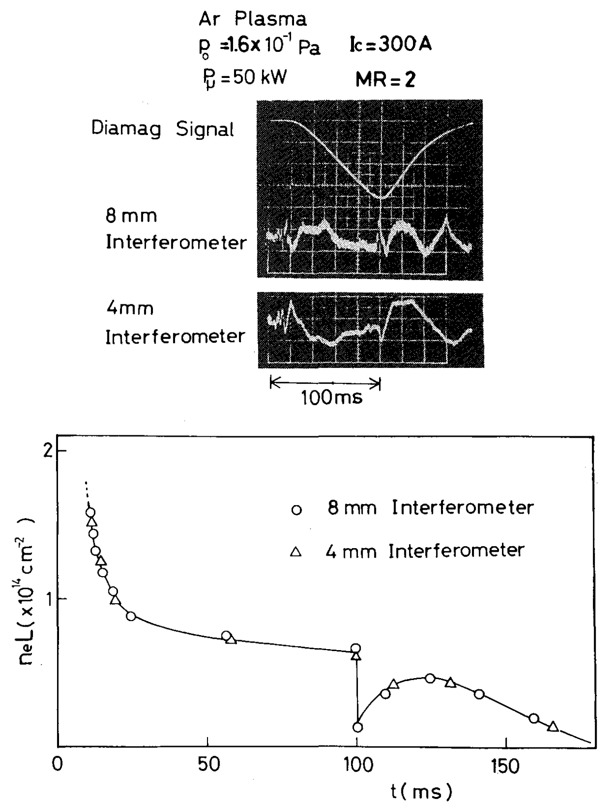

Fig. 3 Time variation of fringe patterns and line density obtained by two interferometers.

just after the shut-off of the power input, n_eL decreases by one order quite rapidly with a decay time of about 180 μs, which is nearly equal to the characteristic shut-off time of the power input estimated from the decay of the output signal of the directional coupler. This result reflects the rapid loss of the bulk plasma produced by the millimeter wave. But n_eL begins to increase again to a value of about $5 \times 10^{14}\,\mathrm{cm}^{-2}$ at $t \simeq 120$ ms and is lost with a long decay time of about 30 ms. This feature is brought by hot electrons still alive in the mirror field. The hot electrons ionize the neutral gas and produce cold electrons even without the millimeter wave power input and decay quite slowly losing their energy by ionization and other elastic and inelastic collision processes during their multiple reflections between the two mirrors.

In the figure n_eL for $t \leqslant 10$ ms is not shown. This is because we can not find the phase difference so clearly. As the reproducibility of the data at each shot is very good, we have examined the variation of the fringe patterns by changing the pulse duration of the Gyrotron power from 1 to 50 ms. Observing each afterglow variation of the fringe we could evaluate n_eL to a shorter time. With this procedure we could distinguish a fringe corresponding to $n_eL = 5 \times 10^{14}\,\mathrm{cm}^{-2}$ in case of 4 mm interferometer.

As for the rapid decrease of n_eL at $t \leqslant 20$ ms we have assumed that the neutral gas pressure might also be lowered rapidly with time. **Figure 4** shows time variations of diamagnetic signal, neutral gas pressure measured by the nude gauge and visible emission by the photodiode. The time scale is enlarged to 100 ms/div to know the overall variation of the data with time. We can clearly find that the neutral pressure signal follows the variation of the visible emission during the power input for 100 ms. Because of the decrease of n_eL in this time interval the visible emission also decreases and these facts are indeed brought mainly by a strong decrease of the neutral pressure with time. At $t = 100$ ms, the pressure seems to be almost zero in the linear scale. It is evaluated to be about 0.03 of the initial filling pressure before the discharge. In the afterglow region, the visible emission shows a similar time variation with n_eL and the gas pressure increases quite slowly to the original value of 1.6×10^{-1} Pa.

Due to the poor conductivity in the gas supply system and to the adsorption of the plasma to the chamber wall, a rapid pumping effect of the neutral gas by the production of a plasma prevents prompt supply of new neutral particles into the vacuum chamber. So that even we can successfully produce a high density plasma corresponding to the cut-off density of the millimeter wave within about 1 ms after the firing of the discharge, it decreases by about one order owing to the lack of supply of neutral

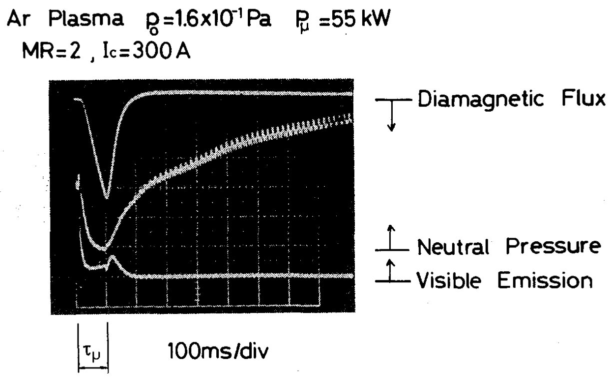

Fig. 4 Time variation of diamagnetic signal, neutral gas pressure and visible emission.

particles to be ionized and the poor confinement of charged particles in a simple mirror field during the power input fo 100 ms.

To compensate for the insufficiency of the gas supply, we are preparing a gas-puff system, by which a quasi-steady state plasma production and heating will be possible for the time interval of 100 ms. The result will be reported by the separate paper.

Figure 5 shows time variation of n_eL for different initial gas pressures. As stated already, all data show similar time variations and the difference is found in the afterglow phase. In the plasma production and heating phase within $t = 100$ ms, n_eL increases with pressure, whose tendency is also drawn on the right of the figure. It should be remarked here that the horizontal axis indicating the gas pressure p_0 is selected as the initial filling pressure in the vacuum chamber. The line density increases with the gas pressure and it has a stronger tendency in the early time such as $t = 10$ ms than in the later time at $t = 99$ ms. In the afterglow phase production of a cold plasma by the residual hot electrons are stronger in a higher pressure, and it clearly reflects the fact that hot electrons, produced by the wave and confined in the mirror field, stay for a longer time in a lower pressure producing cold electrons by the ionization of the neutral gas. When hot electron production rate is larger as well as bulk plasma electrons in a higher pressure, it can be assumed that hot electron temperature is high enough in the afterglow to produce cold electrons with a constant ionization rate. This feature will be discussed again later.

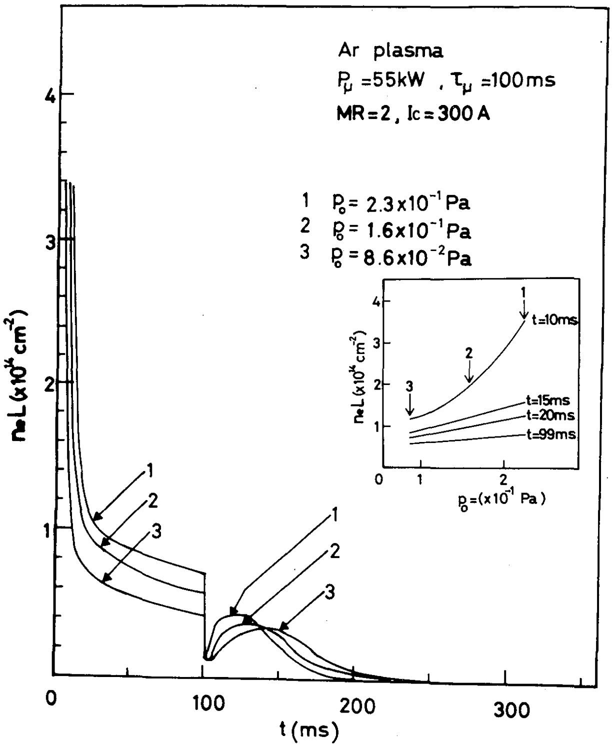

Fig. 5 Pressure dependence of line density variation with time.

Next we have examined dependence of n_eL on the input power of the Gyrotron. **Figure 6** shows the result for two values of MR. When the input power P_μ is larger than 40 kW, n_eL shows almost the same time variation in

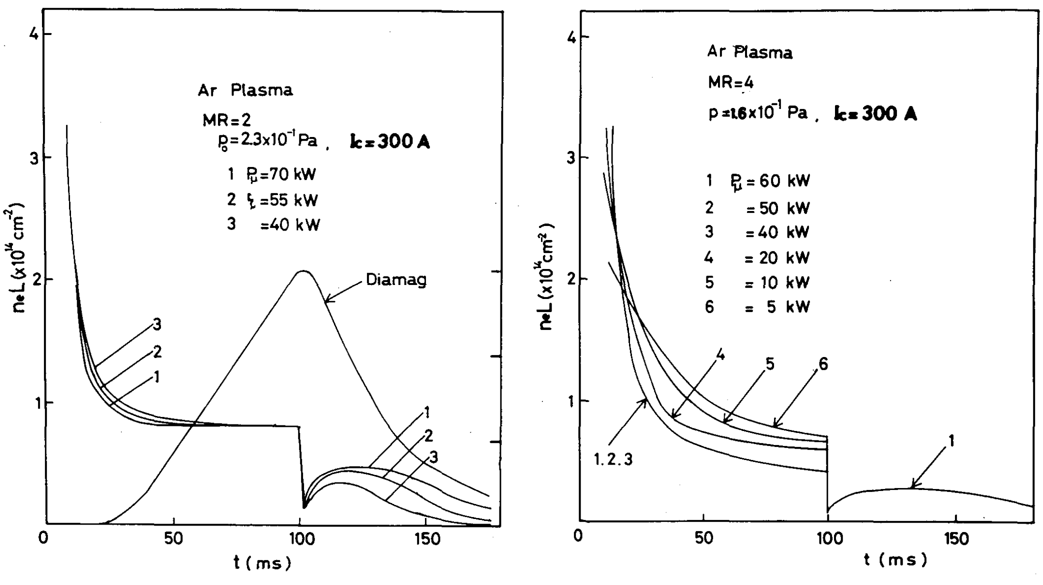

Fig. 6 Power dependence of line density variation with time at two mirror ratios.

the plasma production and heating phase of $t \leqslant 100$ ms in both cases. In the afterglow phase the higher the power input, the larger the value of $n_e L$. It reflects the fact that hot electron density grows with the power input in the plasma production and heating phase.

To determine the electron density n_e averaged over the plasma diameter, a radial intensity distribution of visible emission was measured and it had a bell-shaped distribution with a diameter L in full width at a half-maximum (FWHM) of about 20 cm. In case of $MR = 2$ we can evaluate n_e to be $4 \times 10^{12}\,\mathrm{cm}^{-3}$ in the quasi-steady state during $30 \leqslant t \leqslant 100$ ms from the data in the left figure. It is much lower than the cut-off density ($4.5 \times 10^{13}\,\mathrm{cm}^{-3}$) of the 60 GHz wave, although the initial filling gas pressure is high enough to produce such a high density plasma. This is, of course, due to the rapid decrease of p_0 with time as discussed already. Since p_0 is lowered to about 0.03 of the initial one in this region the neutral particle density should be $2 \times 10^{12}\,\mathrm{cm}^{-3}$. The evaluated n_e value is high enough for us to consider that the plasma is in an almost fully ionized state with a production of intense hot electrons as is observed in the strong increase of the diamagnetic signal in this time interval.

In the right figure we can see a remarkable difference of the time variation of $n_e L$ for $P_\mu = 5$–20 kW. This result is also observed in case of $MR=2$, though not shown in the left figure. The lower the power input, the lower the line density in the early time ($t \leqslant 20$ ms) and the higher in the quasi-steady state ($t \geqslant 30$ ms). This result shows that in the starting phase the plasma does not rapidly reach to a fully ionized state at a low power input in such a high pressure. In the quasi-steady state phase, the pressure drop with time is lower in a lower power input. Hence at a much smaller power around 1–2 kW it may happen that a quasi-steady state of the plasma will lasts for all time interval of the power input and the plasma will be in a partially ionized state without hot electron component in the pressure around 1×10^{-1} Pa. The importance of a high power input is thus clarified for the production of a fully ionized high density and high temperature plasma.

On the difference of the plasma parameters in different mirror ratios we have performed an experiment at a fixed p_μ and p_0 and the result is shown in **Fig. 7**. A remarkable difference is observed both in the production and the heating processes. The line density decreases more sharply in case of $MR = 2$ in the early time of the discharge, although the power input is lower by about 20%. While $n_e L$ in the quasi-steady state reaches to a higher value as well as in the afterglow phase. These results indicate that in case of $MR = 2$ a faster build up of the plasma and a more efficient heating occur resulting in the much more steeper decrease in the gas pressure and the increase

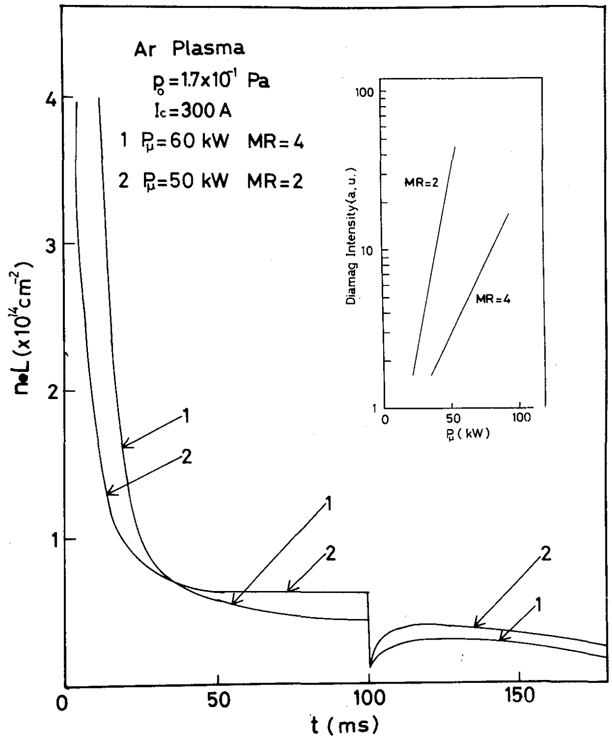

Fig. 7 Comparison of line density variation at two mirror ratios.

of the diamagnetic signal with P_μ. It seems to be contradictory to observe a higher $n_e L$ in the quasi-steady state phase, when the reduction of p_0 with time appears faster.

To interpret the observation reasonably we may first consider that the plasma diameter L is remarkably different in both cases. Another explanation is the assumption of the improvement of the plasma confinement by the higher electron temperature T_e. By the detailed measurements of T_e for the cold and the hot component of electrons we can answer the problem.

As a check of the heating efficiency of the plasma, we have examined in the afterglow phase dependence of the peak $n_e L$ value and the diamagnetic intensity and also their decay time on the input power as shown in **Fig. 8**. The peak $n_e L$ and the diamagnetic signal increase in proportion to P_μ. It is the result at least of the increase in the hot electron density with P_μ. While as for the decay times τ_d and τ_n of the diamagnetic flux and the $n_e L$, respectively, τ_d indicates an increase with P_μ, but τ_n keeps a constant value of 24 ms. The diamagnetic decay time τ_d corresponds to the energy loss time and the decay time τ_n of $n_e L$ to the particle loss time of hot electrons. This tendency indicates that hot electrons are heated further with P_μ as well as increasing its density. Thus the high power input of the millimeter wave is again found to be quite important and very attractive in the production of a high density and high temperature ECR plasma.

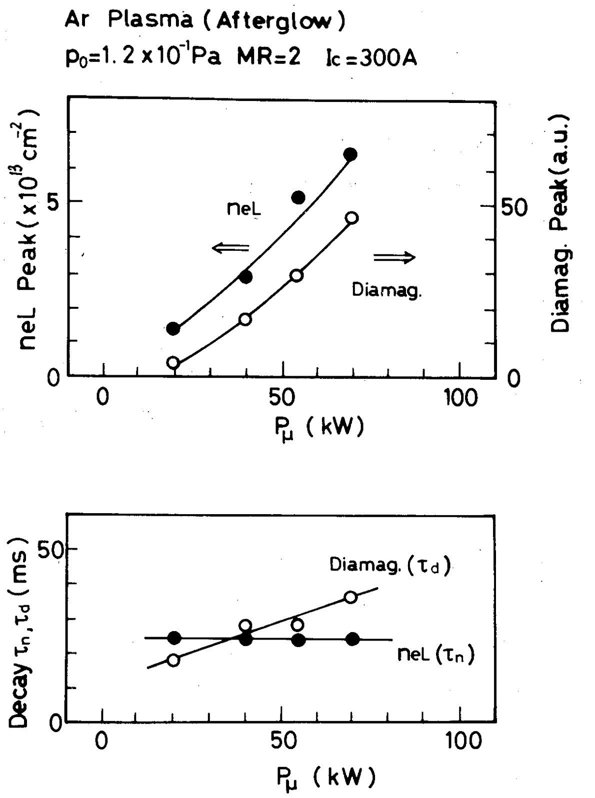

Fig. 8 Power dependence of n_eL, diamagnetic flux and their decay times in the afterglow phase.

4. Conclusion

Time variations of electron density of an ECR plasma in a simple mirror magnetic field were studied in detail. The high power millimeter wave with $f = 60$ GHz was fed for the pulse duration of 100 ms to the vacuum chamber in which Ar gas was filled at a pressure around 1×10^{-1} Pa. In the range of the power input P_μ between 5 and 70 kW it was found that the line density n_eL of the plasma showed a complicated variations with time during the plasma production and heating phase of $0 \leqslant t \leqslant 100$ ms and also in the afterglow phase of $t > 100$ ms. At $P_\mu \geqslant 40$ kW the build up of the plasma finishes within 1 ms after the firing of the discharge and a high electron density comparable to the cut-off density of the 60 GHz wave is obtained. But at $t \gtrsim 5$ ms it begins to decrease with time rapidly and reaches to a quasi-stable state at $t \gtrsim 30$ ms. This result is brought by the strong pumping effect of the neutral gas by the plasma and due to the poor time response of the gas supply system. The electron density n_e in the quasi-steady regime is evaluated to be about 4 ~ 5×10^{12} cm^{-3}, which still indicate a fully ionized state because of the pressure drop to a value of about 3% of the initial one. Also the efficient heating of the plasma acompanied by hot electron production appears in this stage with a steep increase of the diamagnetic signal. In the afterglow phase hot electrons continue to ionize the background neutral gas and vanishes with a long decay time of 30 to 40 ms. They are lost mainly via the collision processes repeating multiple reflections between the two mirrors. The time variation of n_eL was also examined changing external parameters such as the input power of the Gyrotron, the gas pressure, and the mirror ratio. The importance of the high power input was verified to obtain a fully ionized high density and high temperature plasma. A more detailed behavior of the plasma will be reported including hot electron temperature measurement in the next paper.

Acknowledgement

The authors would like to express their gratitude to Profs. S. Kawanishi and T. Yamamoto for their interest and critical comments to this study. They also thank to Dr. K. Oda for his support in the measurement of X-ray.

References

1) Y. Arata et al.: Trans. JWRI 13-2 (1984) 9.