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ECR Plasma in a High Power Millimeter-Wave Beam (Report IV)[†]

– Contribution of Higher Harmonic Resonance Heating –

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Abstract

Remarkable contribution of the 2nd and the 3rd harmonic resonances to the heating of electrons has been clarified experimentally by the radial launch of the millimeter-wave beam to the plasma. While existence of the fundamental (1st harmonic) resonance within the vacuum chamber is verified to be necessary for the efficient ignition of the plasma, irrespective of the wave launching position and/or direction. The heating is observed to be most effective in the resonance zone through which the wave propagates in the first passage, whether it is the 2nd or the 3rd harmonic one.

KEY WORDS: (Electron Cyclotron Frequency) (ECR Plasma) (Gyrotron) (Millimeter-Wave Beam)
(Higher Harmonic Resonance)

1. Introduction

In the former paper[1)] (Report III) difference in the plasma properties was studied in the axial and radial injections of the millimeter-wave beam. A great difference was found in the raidal distribution of the soft x-ray emission because of the spatially limited injection of the wave. As the wavelength of the injected microwave was low enough compared with the dimension of the vacuum chamber, the beam could heat electrons locally when it passed a resonance region within the chamber. At a coil current of $I_c = 300$A, for example, the fundamental resonance zone is distributed in the radial direction at $z = \pm 10$ cm. While the 2nd harmonic zone is found as a plane with a parabolic shape at an off-axial position around $r = \pm 10$ cm and $z = 0$ cm. When the wave was injected from a radial position at the center of the chamber, a typical ring shape was observed in the radial distribution of the soft x-ray emission with a peak intensity around the 2nd harmonic position. This distribution is not altered even when the power input is increased up to 100 kW. While in the case of the axial injection a usual bell-shape distribution was obtained. When the power input was increased, a small hump could be found near the 2nd harmonic zone. In the axial launch it is clear that the fundamental (1st harmonic) resonance plays an essential role in the heating process.

In general it is well known that the fundamental resonance would be most important on the electron heating and the higher harmonic heating might be supplemental. But in our experiment it seems that at least the second harmonic heating can slso be efficient. To check in more detail the contribution of higher harmonic effect to the production and heating of the plasma, we have performed further experiments by varying external parameters widely, whose results are reported in this paper.

2. Experimental Arrangement

The experimental arrangement is the same with the one described in Report II[2)] or III. In this paper typically the data by the radial launch of the wave is reported. The distance of the two mirror coils is kept to be 37.5 cm, by which the mirror ratio is 2. The soft x-ray measurement is performed again using a gas-flow type proportional counter. In Report III the x-ray emission with an energy over 400 eV was studied. In this paper we have lowered the minimum energy range to 100 eV to obtain informations from the bulk plasma as much as possible. We have also measured the time variation of the radial distribution of the x-ray emission to know how the quasi-steady state distribution would be achieved from the start of the plasma ignition.

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3. Results and Discussion

3.1 Plasma ignition at the fundamental resonance

First we were interested in the question whether it was possible to ignite a discharge at the higher harmonic resonance condition without the fundamental resonance. To study this problem measurement of the visible emission and diamagnetic signal was performed by varying the current I_c of the superconducting mirror coils. **Figure 1** shows a typical result in the case of the radial launch of the wave. On the left of the figure intensities of the visible emission and diamagnetic signal are plotted as a function of the coil current. We can clearly find that the visible emission is increased from a coil current of 180 A with a drastic change in its intensity over an order of magnitude. When the power input P_μ from the Gyrotron is low (2 kW), this intensity gradually saturates to a constant value with the increase in I_c. But for the higher input of 35 kW it is saturated promptly to a stronger intensity at $I_c \geqslant 180\,\mathrm{A}$. While on the right of the figure is shown the resonance regions within the vacuum chamber in which a plasma is ignited and sustained. From this map we can find that the fundamental resonance region begins to appear within the chamber when the coil current I_c exceeds 170 A. The 2nd harmonic zones always exist within the chamber showing quite little change in a range of $170\,\mathrm{A} \leqslant I_c \leqslant 190\,\mathrm{A}$. These results indicate that ignition and rapid growth of the discharge will take place only if the fundamental resonance region exists within the chamber. Meanwhile the diamagnetic signal measured at $P_\mu = 35$ kW grows rapidly at $I_c \geqslant 220\,\mathrm{A}$. Over this current the 2nd harmonic region becomes located on the off-axis area in the radial direction such as found at $I_c = 250\,\mathrm{A}$ on the right figure.

To check this problem further the same experiment was performed in the axial launch of the wave, whose result is shown in **Fig. 2**. It should be remarked that the visible emission reveals quite a similar curve with the one in Fig. 1. This result demonstrates that the efficient ignition of an ECR plasma is possible only by the resonance acceleration of electron at the fundamental resonance region irrespective of the wave launching position and/or

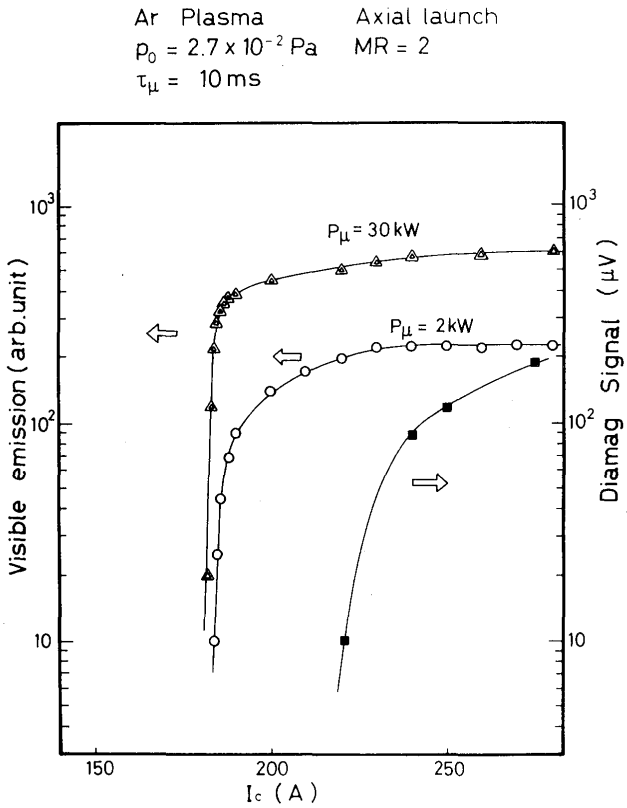

Fig. 2 Variation of the visible emission and the diamagnetic signal with the coil current I_c in the case of the axial injection.

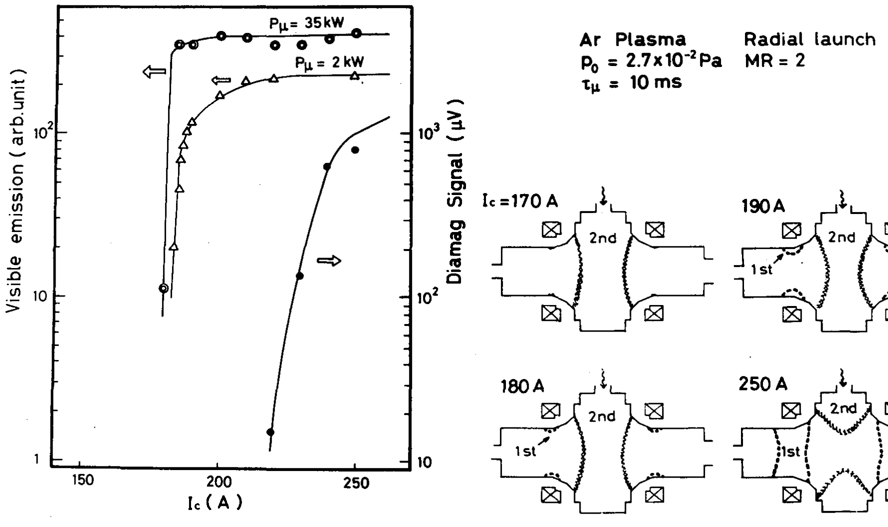

Fig. 1 Variation of the visible emission and the diamagnetic signal with the coil current I_c in the case of the radial injection of the wave to the plasma.

direction. As for the diamagnetic intensity detected at P_μ = 30 kW it also develops from I_c = 220 A, but its intensity is lower about an order of magnitude than the one obtained in the radial launch. This indicates that the second harmonic heating might be more efficient than the fundamental one. But the diamagnetic signal is the space and energy integrated information of the warm and/or hot electron stored energy on the midplane and a detailed interpretation on the heating process is impossible only from this observation.

3.2 2nd harmonic heating

To study the difference in the heating process by each harmonic resonance, the energy dispersive measurement of the soft x-ray emission has been performed with the proportional counter. As indicated in the introduction, it was found in Report III that in the radial launch the intensity distribution had a peak near the 2nd harmonic region and even the 3rd harmonic peak could be observed at a low value of the coil current. While in the axial launch the distribution had essentially a bell-shape with a hot core, and only at a high power input a small hump could be observed near the 2nd harmonic region. **Figure 3** shows such an example of the soft x-ray emission in the radial and axial launches. For all data given below of the radial distribution the numerical calculation of the Abel inversion has not been performed, but various qualitative estimations are possible without losing their correctness. In Report III the distribution was measured for the x-ray with an energy of 400 eV. In this experiment the energy is lowered to 100 eV, and as we can see in the figure a similar distribution is obtained in the time-integrated data over an interval of the power input of 10 ms. Indeed in the radial launch the distribution has a hollow structure and in the axial case a structure with a warm core is clearly found. We note that the peak intensity is stronger in the radial launch and an assumption of a more efficient heating at the 2nd harmonic resonance seems to be correct in correspondence with the data of the diamagnetic signal mentioned above. In the time variation of the distribution also found in the radial input of the wave, we remark that the most efficient heating develops near the 2nd harmonic region even from t = 1 ms after the start of the wave injection.

When the millimeter-wave beam is injected radially at I_c = 270 A, it meets the 2nd harmonic zone at r = 8 cm on the midplane at the first passage through the vacuum chamber. So that it seems that a more efficient heating takes place in this zone, although sufficient number of electrons are supplied from the fundamental resonance region. While in the axial launch the fundamental resonance point on the axis is located at z = 8 cm and the wave passes through this point at the first passage. In this case the 1st harmonic resonance mainly contributes to the heating as well as to the production of sufficient numbers of electrons. In the radial launch the wave input to the chamber is located at r = 22 cm as we can see in Fig. 1 and the distance L_r between this position and the 2nd harmonic point is 14 cm. In the axial launch the wave is injected to the chamber at z = 35 cm and the distance L_z to the fundamental resonance point at z = 8 cm is 27 cm. When we assume the wave may attenuate before reaching to the resonance region by the existence of a cold background plasma, it would be larger in the case of the axial launch, because $L_z > L_r$ and the cold plasma can flow more easily along the axis rather than in the radial direction in the presense of a strong mirror field. On the assumption that the heating efficiency is nearly the same at each harmonic resonance this simple process seems to describe well what we have shown in Fig. 3 as a more intense emission of the soft x-ray at the 2nd harmonic region and a stronger diamagnetic signal in the radial launch of the wave.

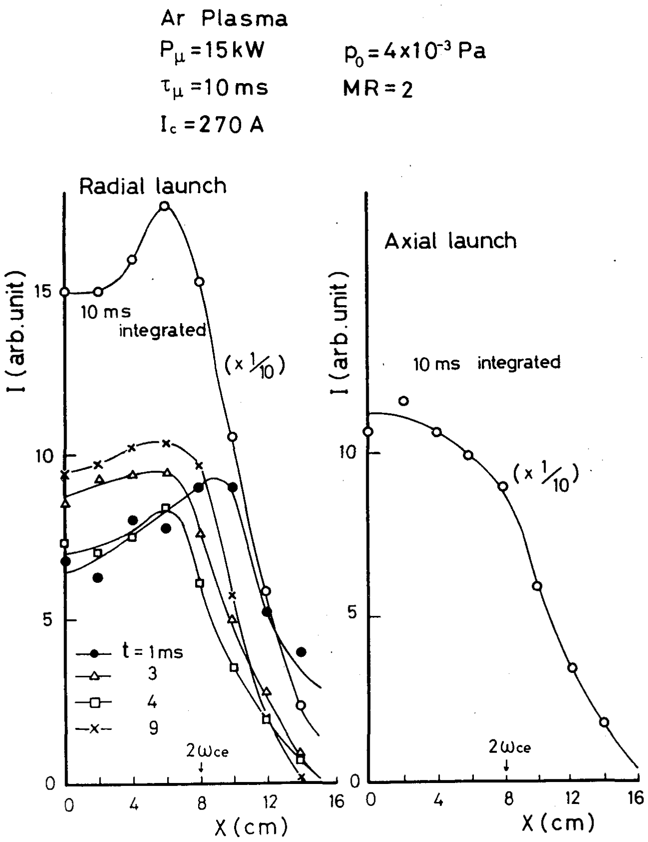

Fig. 3 Radial distribution of the soft x-ray emission with an energy of 100 eV.

Figure 4 shows the radial distribution of the soft x-ray emission for various pressures in the case of the radial launch. At a low pressure of $p_o = 4 \times 10^{-3}$ Pa, the distribution clearly gives a peak intensity at the 2nd harmonic region. When the gas pressure is increased to 3.2

× 10^{-2}Pa it approaches to a bell-shape distribution as if it indicates the disappearence of the 2nd harmonic heating effect. **Figure 5** is the similar distribution in which the data in the positive and negative radial directions is given simultaneously. At a low pressure of 4×10^{-3}Pa it reveals nearly a symmetric distribution in the radial direction. At $p_o = 3.2 \times 10^{-2}$Pa the symmetry begins to be lost, and at $p_o = 6.4 \times 10^{-2}$Pa the distribution becomes clearly asymmetric showing again a peak intensity at the 2nd harmonic resonance position on the side of the wave input. These results indicate that the 2nd harmonic heating is still dominant at a high pressure where the millimeter-wave beam is strongly attenuated by the first passage through the resonance zone in the radial direction.

3.3 3rd harmonic heating

In Report III we noted that in the radial launch the 3rd harmonic resonance can also have a remarkable influence to the intensity distribution of the soft x-ray emission over 400eV. We have continued experiments on this problem and found a very interesting result as shown in **Fig. 6**. In the upper part of the figure is shown the radial distribution of the x-ray emission at $I_c = 230$A and in the lower the data at $I_c = 300$A. The power input P_μ of the radially injected wave is 2 kW with a pulse duration τ_μ of 100 ms. The harmonic resonance points on the midplane is given by arrows in the figure. Indeed the distribution at $I_c = 230$A is quite different from the one obtained

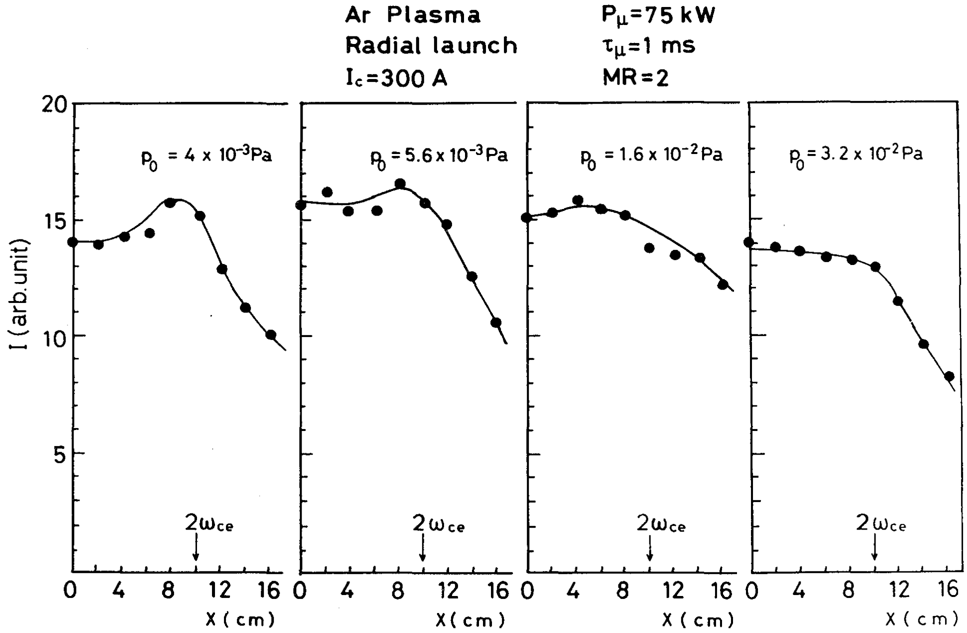

Fig. 4 Radial distribution of the soft x-ray emission for various gas pressure.

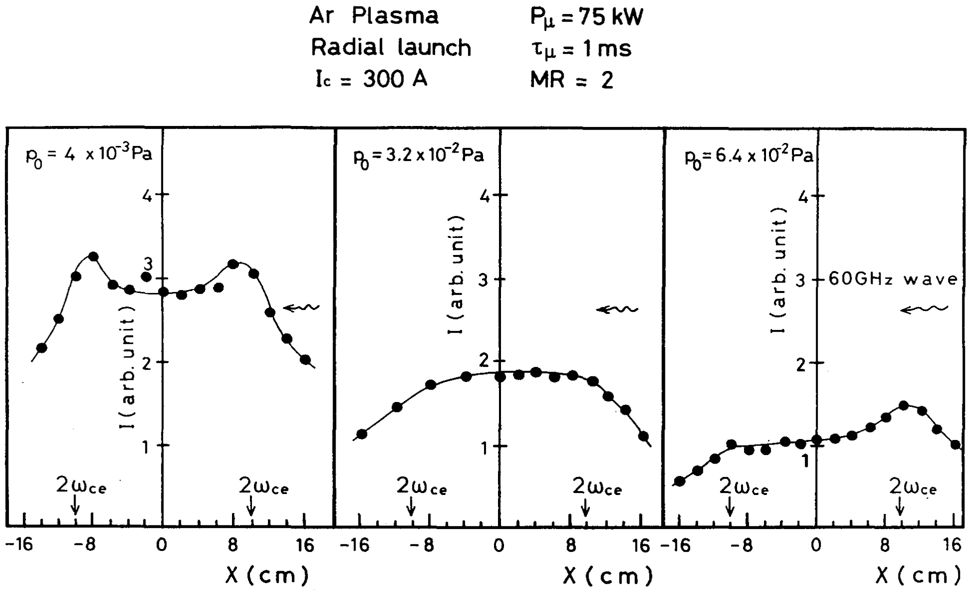

Fig. 5 Radial intensity distribution of the soft x-ray for three values of the gas pressure.

in the former report with an input power of 90 kW and the pulse duration of 1 ms. It seems that nearly the same ring structure is obtained even when the coil current has been varied widely. At I_c = 300 A the distribution has the maximum near the position of the 2nd harmonic resonance. At I_c = 230 A, however, the maximum appears in the middle of the 2nd and the 3rd harmonic positions, which has made us suggest that both resonances might have a comparable contribution for the heating of electrons and gathered the data by varying the input power with the same pulse duration of 1 ms. **Figure 7** shows the result in the case of I_c = 220 A in which the 2nd harmonic zone lies on the axis and the 3rd harmonic is on x (=r) = 12 cm of the midplane. At a small power of 10 kW the maximum intensity appears near the 3rd harmonic zone and the relative intensity at the 2nd harmonic position increases with P_μ. At P_μ = 90 kW we again obtain the same distribution as the one found in Report III; there appear two peaks at both resonances. From this observation we can demonstrate that the 3rd harmonic heating has a comparable contribution as well as the 1st and the 2nd harmonics, when the wave passes through this zone before being attenuated strongly by the plasma.

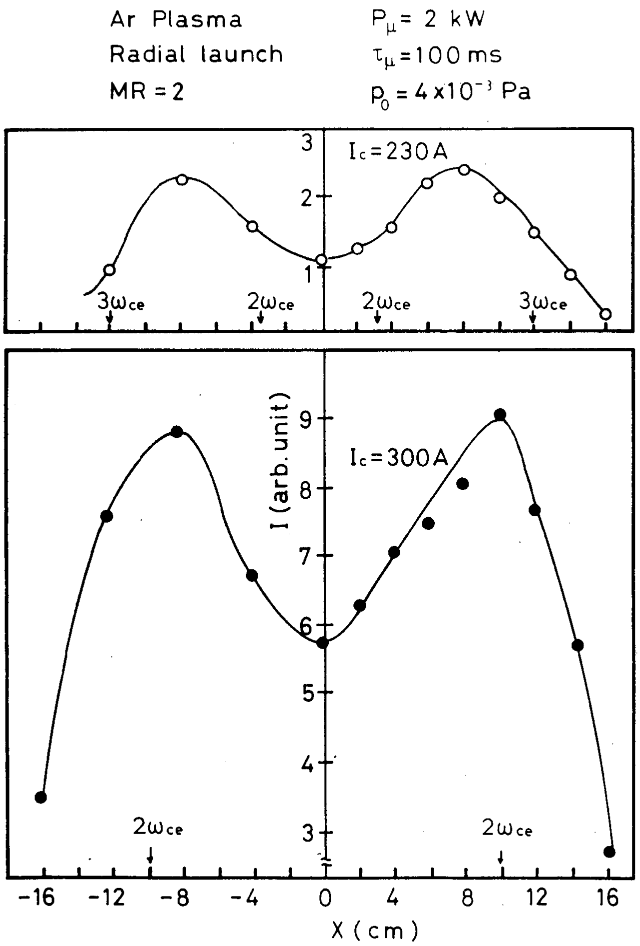

Fig. 6 Radial distribution of the soft x-ray emission at I_c = 230 A and 300 A.

As the time duration of the millimeter-wave is different in Figs. 6 and 7 measurement of the time variation of the distribution was performed at I_c = 220 and 270 A whose result is shown in **Fig. 8**. The power input of 30 kW has been injected for the time interval of 10 ms and distributions at various times after the power input are shown in the figure. The sampling duration for each data is selected to be 1 ms. Similar to the data in Fig. 3 we find

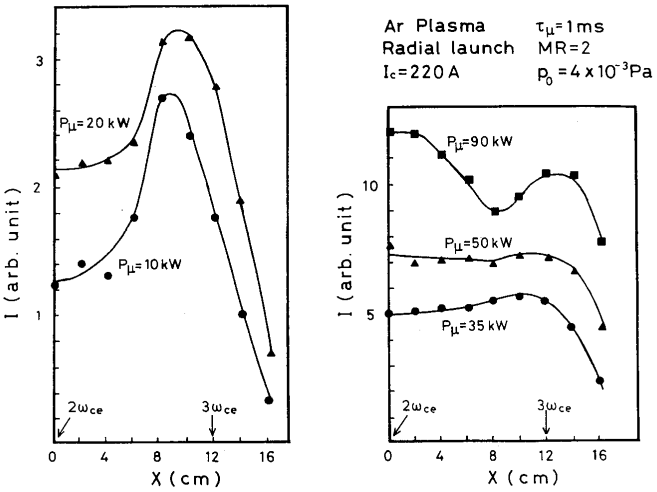

Fig. 7 Distribution of the soft x-ray for various values of the power input P_μ.

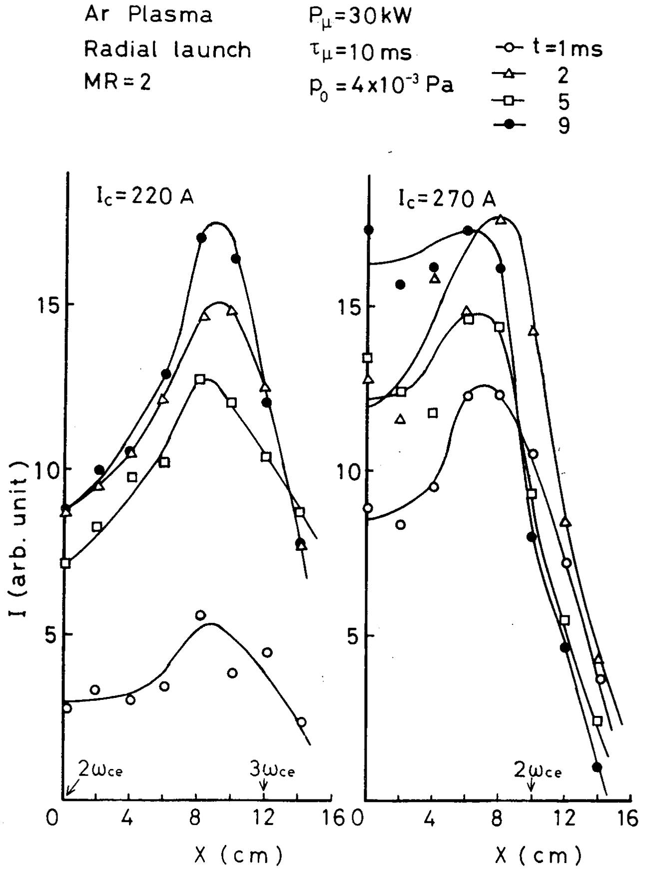

Fig. 8 Time variation of the soft x-ray distribution in the radial direction at I_c = 220 A and 270 A.

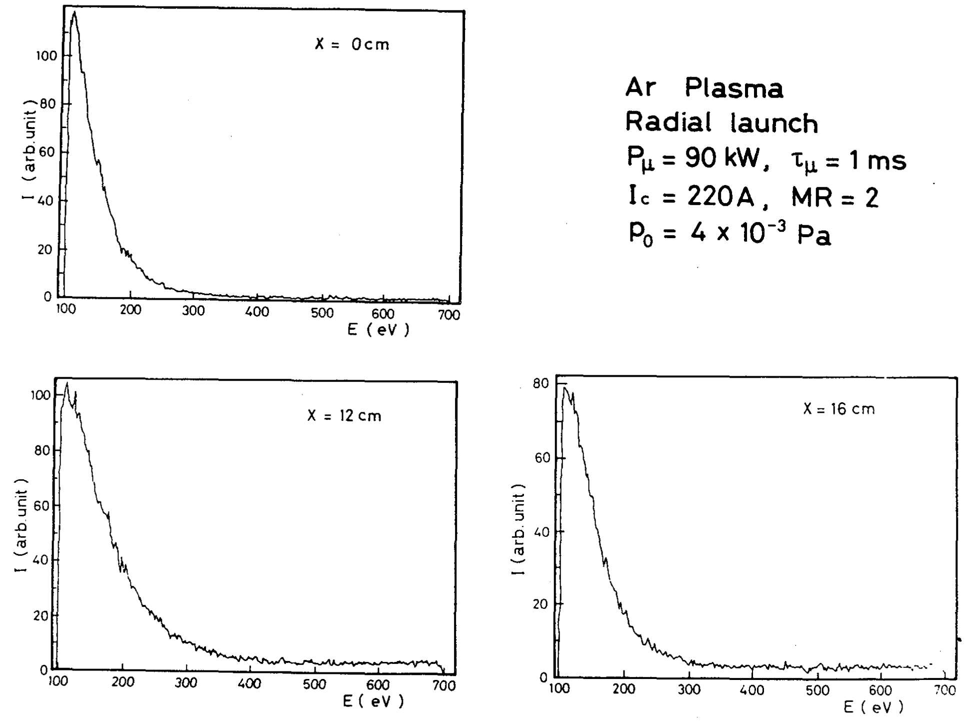

Fig. 9 Energy distribution of the soft x-ray emission at various positions in the radial direction.

again that at $I_c = 220$ A the heating is mainly supported by the 3rd harmonic resonance even in the early stage of the heating such as $t = 1$ ms. While at $I_c = 270$ A the heating is performed by the 2nd harmonic resonance effect. It should be noticed here that the intensity is once decreased at 5 ms after the power input in both cases. In Report II it was described that the build-up of the line density of electrons ceases with a maximum value at a time within 1 ms after the plasma ignition, after which it is decreased due to the strong pumping action of the plasma accompanying a lack of sufficient supply of the neutral gas. At $t = 10 - 20$ ms the density reaches to a quasi-steady value when the power input lasts for a longer time. So that a decrease of the soft x-ray emission after passing a peak value at $t \leqslant 5$ ms corresponds to the decrease of the electron density, and its growth again at $t = 9$ ms which is found in the figure is due to the progress of the heating in a quasi-steady state regime.

So far the discussion has been given using the intensity distribution of the soft x-ray with an energy of 100 eV. To study the process more clearly it is very important to describe on the energy distribution of the emitted soft x-rays. **Figure 9** shows a typical example of the raw data obtained by the proportional counter. The operating condition is the same with the ones in Fig. 7 and the input power P_μ is fixed to be 90 kW. We can clearly find that the hottest distribution is obtained at x (=r) = 12 cm corresponding to the 3rd harmonic resonance position. But the intensity at 100 eV is stronger at $x = 0$ cm as we have plotted in Fig. 7. This indicates that the heating is mainly supported by the 3rd harmonic resonance effect rather than the 2nd harmonic one, probably due to the efficient absorption of the wave energy at the first passage through the 3rd harmonic zone. The 2nd harmonic zone will play a suplementally role in the heating in this case. To evaluate the electron temperature from these data we need much care, as the spectral sensitivity of the detector varies drastically in this energy range and the spectral resolution is not good. We are now checking these problem and at present does not give further comment. But only from these qualitative estimations discussed above on the soft x-ray emission, it is concluded that higher harmonic resonances can greatly contribute to the heating process of an ECR plasma in a mirror field.

Acknowledgement

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