The influence of a transverse magnetic field on a glow discharge tube

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The positive column of low pressure discharge has been used for an illuminating lamp, a gas laser and a plasma display device. When a transverse magnetic field is applied on a positive column, the plasma parameters such as an axial electric field, an electron temperature and an electron density are increased. As a result, the light intensity of a gas laser, for example, is increased with the transverse magnetic field. In this paper, the experimental results on such plasma parameters and the light intensity are measured for the cylindrical discharge tube filled with neon gas. The tube used is 40 mm in diameter and the discharge current is 20-60 mA. The magnetic field is varied from 0 to 1000 G. It was found that the above mentioned plasma parameters were increased with the magnetic field, and that this effect is more remarkable at lower gas pressure. The experimental results were discussed qualitatively with the wall effect of electrons in the positive column.

1. Introduction

When a steady uniform positive column of a low pressure discharge is applied with a transverse magnetic field, such various changes as the increase in the anode potential and the intensity of radiation take place. These phenomena are interesting from the viewpoint of the control of the intensity of radiation and of the spectrum from the discharge tube like a gas laser or a plasma display.

Penning[1] studied the characteristics of the glow discharge of the coaxial cylinder in a crossed electric and magnetic field in helium and neon. McBee and Dow[2] investigated the potential distribution in an unconfined glow discharge in a transverse magnetic field in the air. Sen and Gupta[3] also investigated experimentally the variation of the discharge current in a transverse magnetic field in helium, neon, hydrogen and air. There have been, however, no reports on the measurements of the intensity of radiation and its radial distribution in a positive column in a transverse magnetic field. On the other hand, these phenomena have been theoretically treated by Beckman[4] on the basis of the earier theory of Tonks and Allis[5] . According to the Beckman's theory, the axial electric field and the electron temperature in the positive column increase with increase of the transverse magnetic field. But the direct measurements of the electron temperature and the axial electric field have been reported littl so far[6)-9)].

In this paper the results of the measurements on the intensity of radiation of the positive column and its radial distribution in a transverse magnetic field by an optical instrument and those on the electron temperature, the axial electric field and the wall loss by means of probes are presented. Then the experimental results are qualitatively discussed.

2. Experimental procedure

The discharge tube used was cylindrical with a plasma of about 200 mm in length and of 40 mm in diameter as shown in **Fig. 1(a)**. It consisted of a disc anode of molybdenum, a hollow cathode of nickel and three probes of tungsten. The probes were two cylindrical probes and a ring one. The cylindrical probe was 0.2 mm in diameter and 2.0 mm in length, sheathed in the glass, and was placed with a spacing of 20 mm in the axial direction. They were inserted into the plasma at each place as shown in Fig. 1(a). The ring probe was 0.2 mm in diameter and was arranged in a circle inside the wall. The discharge tube had an end window to observe the intensity of radiation and its radial distribution in the positive column. They are also shown in Fig. 1(a). The discharge tube was pumped to 10^{-7} Torr by means of an oil diffusion pump with liquid N_2 trap, and adsorbed gases in the wall and electrodes were removed after baking process. Gas used for measurement was neon, and its purity was 99.99%. The discharge current I_b was 20–60 mA and the gas pressure p was varied from 1.5 to 10.0 Torr. The magnetic field B was provided with the magnetic poles of 140 mm ×140 mm. It was applied perpendicularly to the axis of a positive column. The magnetic field was

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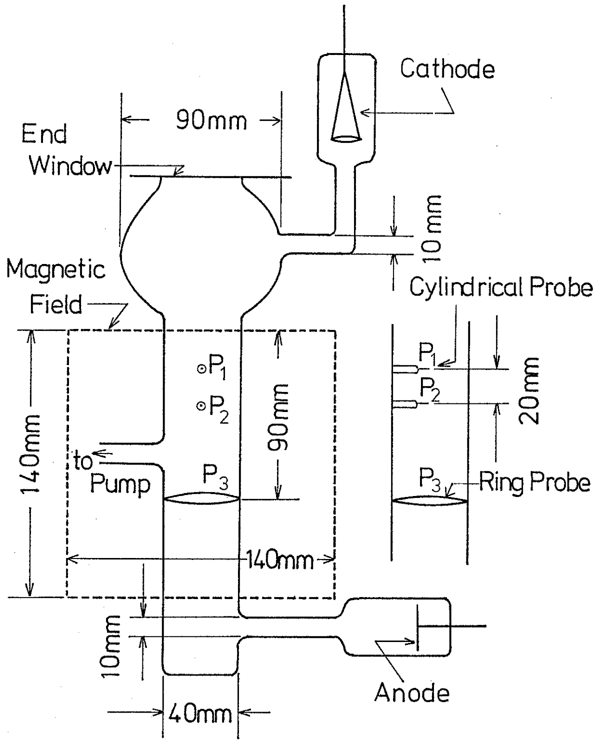
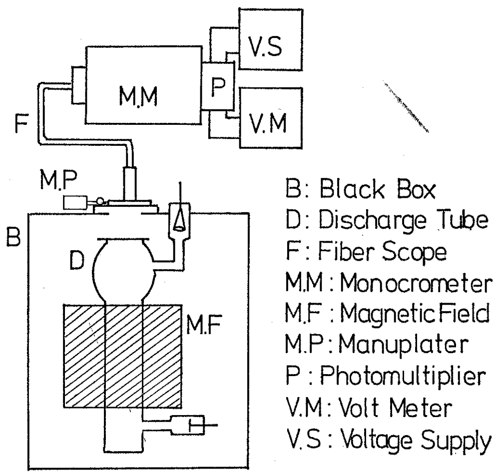


(a)



(b)

Fig. 1 (*a*) *Schematic diagram of the discharge tube.*
(*b*) *Schematic diagram of the measurement of the radiation*

changed from 0 to 1,000 Gauss. The intensity of radiation and its radial distribution in the positive column was observed from the end window of the discharge tube. The radiation light from the positive column is guided to the monocrometer by a glass fiber scope and then is accepted by a photomultiplier. The output voltage of the photomultiplier is measured by a high gain valve voltmeter. The fiber scope is 1.0 mm in diameter and is movable in radial direction of the positive column.

The electron temperature was measured by the floating double probe method by Dote[10] which was modified from the equivalent resistance method by Johnson and Malter[11]. This method is applicable to the case of a weak magnetic field when the Larmor radii of electrons are larger than the probe radius and also Debye length[12)-13)]. This condition was satisfied in all the present discharge plasma and thus the electron temperature was obtained from the method of the solution of zero magnetic field. The current-voltage characteristics of the double probe measurement were displayed on the X–Y recrder.

The axial electric field of the positive column was obtained from the floating potential difference between two cylindrical probes. This potential difference corresponds to the space potential one in the plasma because of the axial uniformity of the positive column which has been experimentally confirmed during every measurement of the plasma parameters. One of the factors which cause the increase of the plasma parameters and the intensity of radiation under the influence of the transverse magnetic field is considered to be the increase of the wall loss by the magnetic field. Therefore, it is necessary to measure the wall loss of a positive column, in a transverse magnetic field. The center of a positive column, however, is deflected to one side of the wall and thus the energy loss of electrons at the wall increases on this side and decreases on the opposite side. Therefore, the ring probe was used for the measurement of the total wall loss instead of the plane probe which is usually used for the measurement of the wall loss[14)-15)]. Total wall loss was able to obtain from the electron current to the ring probe at the wall potential, which was measured by the ion saturation current region of the single probe characteristics when the cathode potential was standard[16)].

3. Experimental results

3.1 The intensity and its radial distribution of radiation

The radial distribution of the intensity of the radiation in a positive column for different transverse magnetic fields is shown in **Fig. 2** when the discharge current is 60 mA and the gas pressure is 2.0 Torr. It is evident that the radial distribution intensity is deflected by the transverse magnetic field and the maximum intensity of radiation is increased with the transverse magnetic field. The deflection of the center of the intensity when the magnetic field is zero is caused by the influence of the radiation parts of the positive column where branch to the anode is fitted up perpendicularly to the axes of the positive column and the magnetic field as shown in Fig. 1. The radial distribution of the intensity of radiation for different gas pressures is shown in **Fig. 3** when the magnetic field is 800 Gauss. From the figure, we find that the distribution of intensity of radiation is deflected and the maximum value of its intensity is increased under the influence of the magnetic field as the gas pressure decreases.

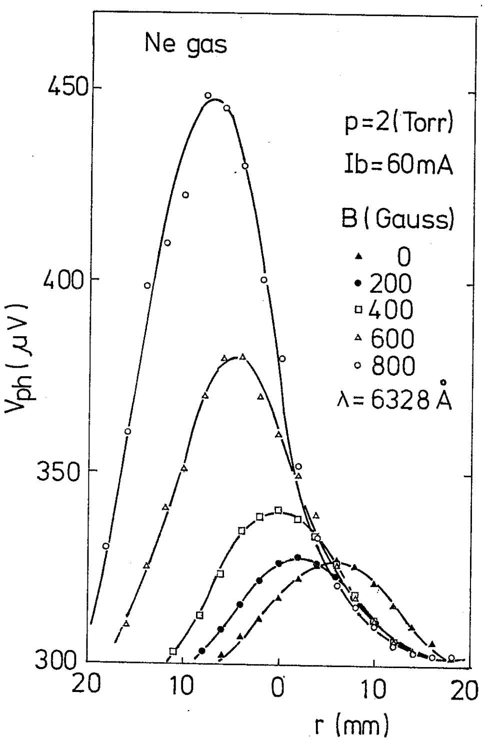


Fig. 2 *The distribution of radiation in a transverse magnetic field.*

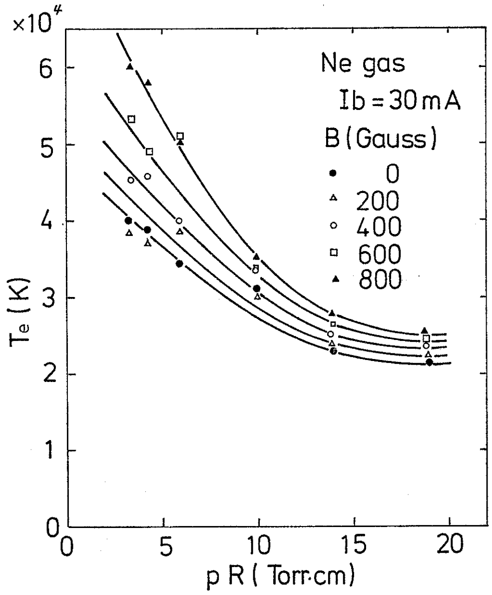


Fig. 4 *Electron temperature dependence on the transverse magnetic field as a function of the product of the gas pressure and the tube radius for neon of 30 mA in the discharge current.*

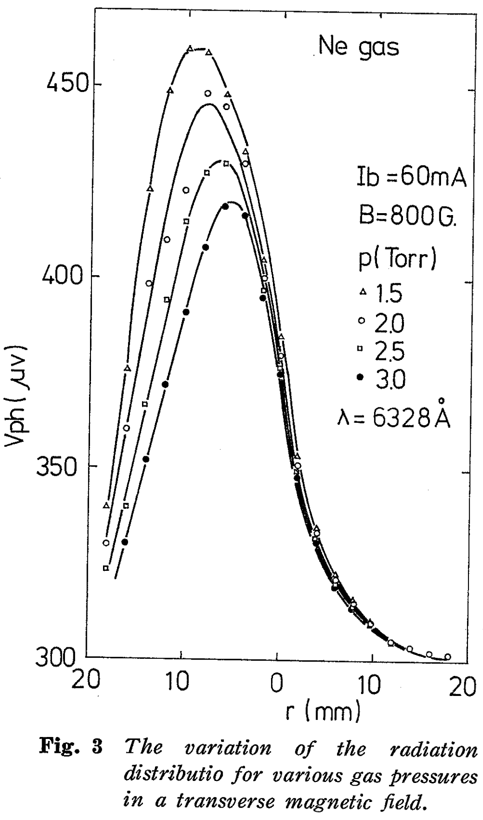


Fig. 3 *The variation of the radiation distributio for various gas pressures in a transverse magnetic field.*

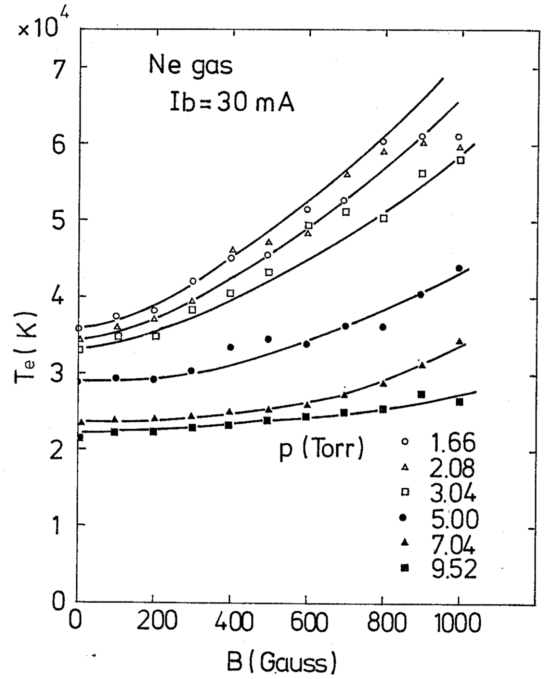


Fig. 5 *Electron temperature depence on various gas pressure as a function of the transverse magnetic field field of 30 mA in the discharge current.*

3.2 Electron temperature

The variation of electron temperature T_e against different values of the transverse magnetic field, when a discharge current was 30 mA, was plotted as a function of the product of the gas pressure p and the tube radius R as shown in **Fig. 4.** The common trend of the curves in that after the slow increase from the lower limiting value, the electron temperature tends to increase steeply as the product decreases. In **Fig. 5,** the variation of the electron temperature against different values of the gas pressure at the discharge current of 30 mA was plotted as a function of the transverse magnetic field. We find in this figure that the electron temperature rises monotonically with the increase of the transverse magnetic field and that this effect is more remarkable in lower gas pressure. From the experimental results of electron temperature when the discharge current was changed, it was found that the electron temperature was nearly independent of the discharge current.

3.3 Axial electric field

The ratio of the axial electric field E_z to gas pressure p at a discharge current of 30 mA was plotted for various transverse magnetic fields as a function of the product pR as shown in **Fig. 6.** In **Fig. 7,** the variation of the ratio of the axial electric field to the gas pressure for various gas pressures is plotted as a function of the transverse magnetic field. From the figures, it is evident that the ratio of the axial electric field to the gas pressure is also increased as the transverse magnetic field does, and that its effect is also remarkable at lower gas pressure. In **Fig. 8,** the variations of the axial electric field to the gas pressure with a discharge current is plotted as a function of the transverse magnetic field. It is found that the ratio of the axial electric field to the gas pressure is also nearly independent of the discharge current.

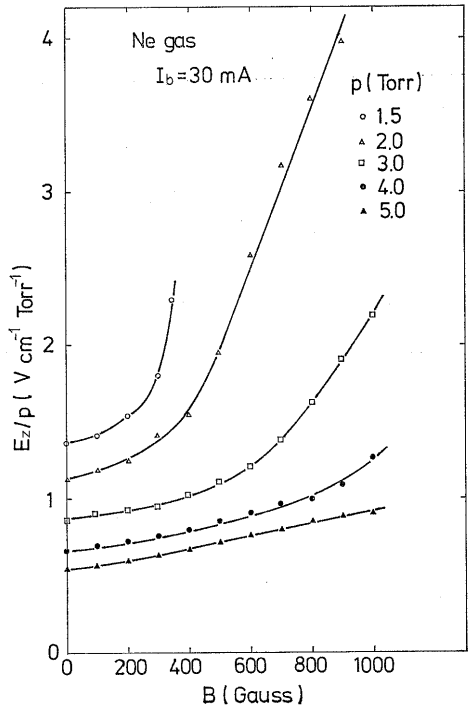


Fig. 7 *Axial electric field dependence for various gas pressure as a function of the transverse magnetic field of 30 mA in the discharge current.*

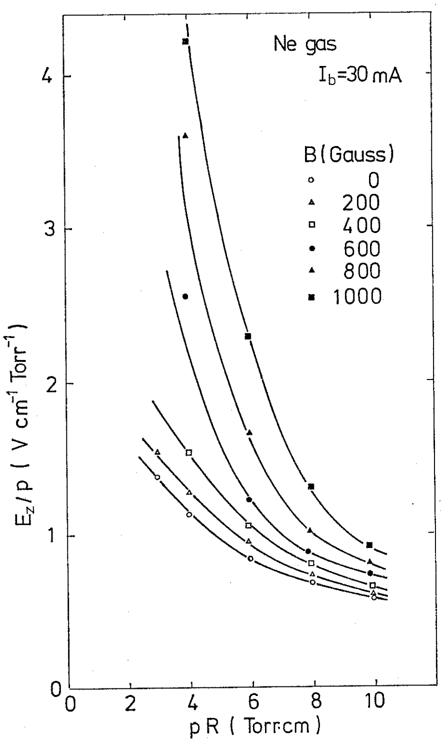


Fig. 6 *Axial electric field dependence on the transverse magnetic field as a funtion of the product of the gas pressure and the tube radius for neon of 30 mA in the discharge current.*

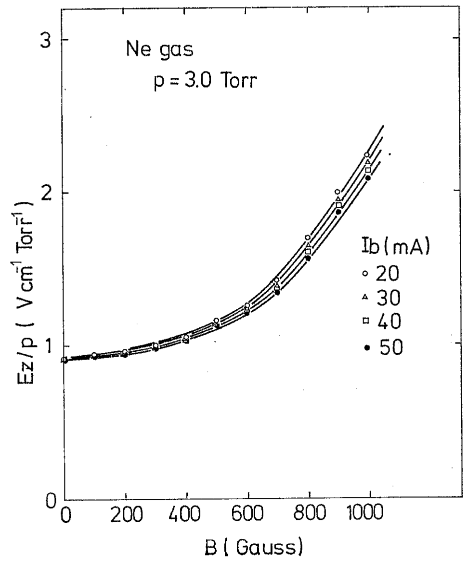


Fig. 8 *Axial electrical field dependence for various discharge current as a function of the transverse magnetic field of 3.0 Torr in in the gas pressure.*

3.4 The total wall loss of electrons

In **Fig. 9**, the examples of the voltage-current characteristics, when the ring probe is used as a single probe, is shown at the gas pressure of 2.5 Torr with a discharge current of 30 mA for various transverse magnetic fields. In this figure, the voltage, when the probe current is zero, is equivalent to the wall potential V_w. Therefore, the value I_e

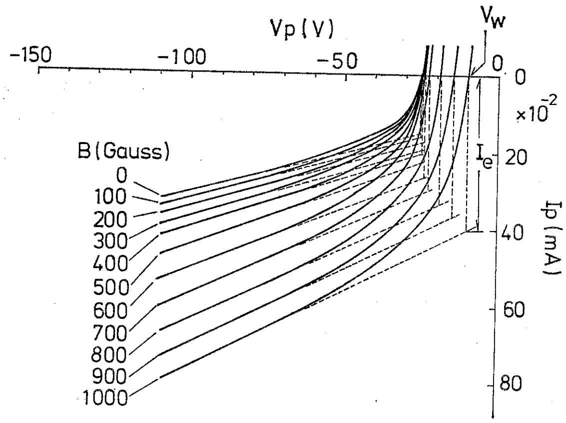


Fig. 9 *The example of the ion saturation current in a transverse magnetic field. The discharge current is 30 mA with the gas pressure 2.5 Torr.*

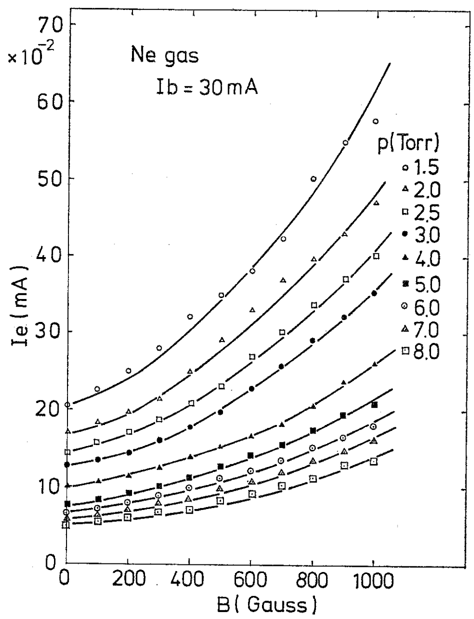


Fig. 10 *The electron current to the ring probe at the wall potantial as a function of the transverse magnetic field for various gas pressures.*

of the ion saturation current when the curve is extraporated to the wall potential is equal to that of both an ion current and an electron current flowing to the ring probe. Because the electron current flowing to the probe is proportional to the energy loss of electrons to the wall, the total wall loss can be measured by the ring probe. In **Fig. 10**, the variation of the electron current at the wall potential with different gas pressure is shown as a function of the transverse magnetic field. From the results the wall loss increases as the transverse magnetic field does and its effect grows noticeably with the decrease of the gas pressure.

4. Discussion

When a steady uniform positive column of a low pressure discharge is applied by a transverse magnetic field, the charged particles drift across magnetic lines of force in cycloidal motion among their collisions with gas atoms. This increases the flow of electrons in one side of the wall and decreases the flow of them in the opposite side, however, the increase of the flow in one side of the wall exceeds that in the opposite side. Therefore, the total flow of electrons to the wall increases as the transverse magnetic field does. The electrons to the wall lose their energy by the recombination with ions on the wall. As a result, the total wall loss increases as the transverse magnetic field does as shown in Fig. 10.

According to the ambipolar diffusion theory by Schottky[17], the number of electrons flowing to the wall in a unit length of the positive column is balanced with that of electrons created in the volume of the column. Therefore, the increase of the wall loss of electrons is supplied by the increase of the creation by the ionization of gas atoms. The ionization of gas atoms is due to the collisions by the electrons of higher energy than the ionization potential, and assuming that the electron energy distribution is Maxwellian, the number of electrons in such a state is proportional to the electron temperature. Thus the creation of electrons in a positive column is monotonically increased with the increase of the electron temperature. As a result, the electron temperature increases as the transverse magnetic field does. Such an effect is strengthened in lower gas pressure because of the great amount of electron diffusion flowing to the tube wall.

The axial electric field of a positive column is derived from the power balance equation that the energy gain of electrons from the field balances with its energy losses by the diffusion of electrons to the wall and by the collision of electrons with neutral gas atoms[18]. The energy loss of electrons by the collision increases with the rise of electron temperature because inelastic collisions considerably increase with the rise of electron temperature. The collision loss also increase with the rise of the transverse magnetic field. These increases of the wall loss, the electron temperature and the collision loss cause the axial electric field to rise in the power balance equation in a positive column. Moreover, the cycloidal motion of electrons in a magnetic field decreases the axial mobility of electrons in a positive column. This effect also acts as a factor to raise the axial electric field. In lower gas pressure, the axial electric field increases noticeably because such plasma parameters are very effectively influenced with the magnetic field owing to the long mean free path of electrons in cycloidal motion.

The total intensity of radiation from the positive column is proportional to the total number of the excited gas atoms which transfer from the upper excited level to the lower excited one. The most of the excited gas atoms depend on the excitation from the ground state gas atoms. The excitation occurs at the collisions between the ground state gas atom and the electrons of higher energy than the excited energy level. The number of electrons of higher energy are proportional to the electron density and electron temperature. Since the electron temperature is uniform in a positive column, the number of excitation is mainly proprtional to the electron density. As a result, the intensity of radiation is proportional to the electron density. As is derived by Beckman[4], the electron density is deflected by the influence of the transverse magnetic field and thus the intensity of radiation is also deflected by the transverse magnetic field.

On the other hand, the discharge current of a positive column is proportional to the product of the axial drift velocity of electrons and the number of electrons in a positive column. Since the axial drift velocity is decreased with the increase of the transverse magnetic field under the influence of the cycloidal motion of electrons, the number of electrons increases as the transverse magnetic field does. Therefore, the intensity of radiation considerably increases as the transverse magnetic field does.

5. Conclusion

It can be concluded that the electron temperature, the axial electric field and the intensity of radiation in the positive column are increased with the increase of the transverse magnetic field. The distribution of the radiation intensity is also deflected by the transverse magnetic field. It was found to be clear that these effects are more remarkable at lower gas pressure and that the plasma parameters are nearly independent of the discharge current. These phenomena are qualitatively understood by the increase of the wall loss under the influence of the transverse magnetic field. The deflection of the center of the radiation intensity are explained by the deflection of the electron density in a transverse magnetic field.

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