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Current Sustaining by RF Travelling Field in a Collisional Toroidal Plasma

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Abstract

The relation between the current generation by RF travelling field and the accompanied power absorption is studied in a collisional toroidal plasma, parameters being phase velocity and filling gas pressure or electron collision frequency. It is observed at a low magnetic field that the current is proportional to the plasma conductivity and an effective electromotive force, which is a new concept introduced on the basis of fluid model; the electromotive force is proportional to the absorbed RF power and inversely proportional to the plasma density and the phase velocity of the travelling field.

§1. Introduction

The toroidal plasma current generation by an RF travelling field is interesting because the current can be excited without an electric field induced by a magnetic induction. There are several experiments[1-5] which demonstrated the current generation by an RF travelling field. Among them, a recent study carried out by Fukuda et al.[6] revealed the fundamental properties of the current generation in a low magnetic field; there is an optimum of toroidal field strength for the current generation, and this phenomena is related to the RF field penetration into the plasma, a local assembly of excitation system can be also used with a reasonable efficiency.

For a more precise understanding of the physical mechanism, however, further experiments will be necessary. The relation between the generated current and the absorbed power is also an example of the basic and important problems. It is pointed out[7] that the RF power absorption by electrons is necessary for the production of the plasma current by means of RF travelling field. This is because the momentum transfer from the RF field to electrons occurs as a result of RF power absorption.

This current generation is expected to be applicable to current sustaining of a steady tokamak.[8] In this case, the relation between the current and the RF absorbed power will also be important.

In this paper, we study on this fundamental relation in a collisional plasma at a low magnetic field and introduce the concept of an effective electromotive force that plays an important role in the current generation. We present at first a fluid model for the current generation and then the experimental results on the relation between the generated current and RF power absorbed by plasmas.

§2. Fluid Model of Current Generation

We consider a collisional uniform plasma, in which the electron collision frequency ν_e is higher than the wave frequency ω of the RF travelling field. Here we shall neglect ion motions assuming that ion mass is large enough. In such a plasma, fluid model may be used. The equation of motion for electrons is

$$n\, m \frac{dV_e}{dt} = -\, ne(\tilde{E} + V_e \times B\,) - n\, m\, \nu_e\, V_e \qquad , \qquad (1)$$

where n is the electron density, m is the electron mass, V_e is the velocity of the electron fluid, $\tilde{E}$ is the RF electric field and B is the magnetic field composed of static field B_o and RF field $\tilde{B}$. In the equation ν_e is the collision frequency defined by

$$\nu_e = \nu_{ei} + \nu_{en} + \nu_{ion} \qquad ,$$

where ν_{ei} is the electron-ion collision frequency, ν_{en} is the electron-neutral collision frequency and ν_{ion} is the frequency of collision which causes the ionization.

Averaging eq.(1) over space and time, we obtain the following equation for the steady state,

$$<\tilde{\rho}\, \tilde{E}> + <\tilde{J} \times \tilde{B}> \; = -\, n\, e\, \eta\, J_{DC} \quad , \qquad (2)$$

where $\tilde{\rho}$ is the oscillating component of charge density, $\eta = m\nu_e/ne^2$ is the plasma resistivity and $\tilde{J}$ and J_{DC} are the RF and the DC components of the plasma current, respectively. The angular bracket in the equation indicates the average over time and space of RF components.

The right hand side of eq.(2) means the frictional force produced by collisions. Accordingly we may regard the two terms in left hand side of eq.(2) as the electromotive force due to the RF travelling field.

If we assume the RF field travelling with the dependence of the form exp(iKr - iωt), we obtain using Maxwell equation,

$$\langle\tilde{\rho}\,\tilde{E}\rangle + \langle\tilde{J} \times \tilde{B}\rangle = \frac{\langle\tilde{J}\cdot\tilde{E}\rangle}{V_p}\,\frac{\mathbf{K}}{K} \qquad (3)$$

where K is the wave number of the RF field and $V_p = \omega/K$ is the phase velocity. The quantity $\langle\tilde{J}\cdot\tilde{E}\rangle$ means the RF power dissipation p_a in the plasma. Accordingly, equation (2) is rewritten as

$$\frac{p_a}{J_o}\,\frac{\mathbf{K}}{K} = \eta\, J_{DC} \quad , \qquad (4)$$

where $J_o = -neV_p$. This is the basic equation for the current generation by the RF travelling field.[8,9] The above electromotive force can also be obtained from Maxwell's stress tensor.[7] The equation indicates that the electromotive force is generated when the RF power is absorbed by the plasma, and that amount of the force is inversely proportional to V_p provided that p_a is constant. Since the power dissipation $\langle \tilde{J} \cdot \tilde{E} \rangle$ is a general one, there is no restriction on the absorption mechanism; the dissipation may be due to collisions[10] or wave excitation.[3,7,8]

If we integrate eq.(4) along plasma column under the assumptions that K is in the z-direction and that η and J_o are uniform across the plasma column, we have in the right hand side the voltage due to the frictional force for the DC current, or voltage drop in terms of electric circuit. Therefore, we may consider the integral of p_a/J_o to be the effective electromotive force for J_{DC}. Here we may note that with the decrease of collision frequency ν_e, η and p_a will tends to zero and then the voltage source representation stated above will become inadequate; in this case the trapped particle model[11] or the current source representation will be suitable. Thus we see that the representation of this voltage source is applicable for a collision dominant plasma.

In order to understand the mechanism of the current generation due to RF power absorption, we consider a simple case. An electromagnetic field with TE mode is travelling in a cylindrical plasma; the field consists of components of RF magnetic field ($\tilde{B}_r$, 0, $\tilde{B}_z$) and RF electric field (0, $\tilde{E}_\theta$, 0). The field travels in the z-direction along the static magnetic field. In vacuum the electric field $\tilde{E}_\theta$ oscillates out-of-phase with $\tilde{B}_z$ and in-phase with $\tilde{B}_r$. The magnetic field, composed of B_o and $\tilde{B}_z$, forms a train of mirror field which travels with V_p.

From eq.(1), the RF current $\tilde{J}_\theta$ in a plasma is given by

$$|\tilde{J}_\theta| = \frac{|\tilde{E}_\theta|}{\eta} \frac{\nu_e^2}{\omega_{ce}^2} \cos\phi, \quad \text{for} \quad \omega \ll \nu_e \ll \omega_{ce} \quad , \tag{5}$$

and

$$\phi = \tan^{-1} \frac{\omega}{\nu_e} \quad ,$$

where ω_{ce} is the electron cyclotron frequency and ϕ is the phase angle between $\tilde{E}_\theta$ and $\tilde{J}_\theta$. In a collision dominant plasma, $\tilde{J}_\theta$ oscillates nearly in-phase with $\tilde{E}_\theta$. Then the RF power dissipates in the plasma. A force $\tilde{F}_z$ acting on electrons in the z-direction is given by $\tilde{F}_z = -\tilde{j}_\theta \times \tilde{B}_r$. Since $\tilde{E}_\theta$ oscillates in-phase with $\tilde{B}_r$, the net force is generated in the z-direction. In Fig.1, an illustrative picture for the current generation is shown. The force $\tilde{F}_z$ is distributed in the same direction in every magnetic mirror. Thus a steady electron flow is expected to be generated.

It is known that the RF power absorption can also be calculated on the basis of dielectric tensor. For $\omega_{pe} \gg \omega_{ce} \gg \nu_e \gg \omega$, we have the following power absorption,

$$p_a = \frac{\omega}{8\pi} \mathrm{Im}(\varepsilon_{\theta\theta}) |E_\theta^2| = \frac{1}{8\pi} \frac{\omega_{pe}^2}{\omega_{ce}^2} \nu_e \, |E_\theta^2| \quad , \tag{6}$$

where ω_{pe} is the electron plasma frequency. When the RF travelling field couples with a plasma wave, the power absorption will increase because of the enhanced electric field. The power of eq.(6) equals to that obtained from $\langle \tilde{J} \cdot \tilde{E} \rangle$ of eq.(5). Therefore we see that the power calculated from eq.(6) may be used in eq.(4). From eq.(6), the electromotive force is expected to be small in a low collisional plasma ($\nu_e < \omega$). In this region, however, it will be necessary to consider the collisionless power absorption rather than the collisional damping, and the power absorption given by eq.(6) will be modified.[12)]

§3. Experimental Procedure

The experiments were performed on a toroidal device named Synchromak. Details of the device were given elsewhere.[6)] The schematic diagram of the device is shown in Fig.2. The vacuum vessel is a glass tube with a major radius of 25 cm and minor radius of 5 cm. The plasma is limited by a metallic limiter of 4 cm in radius. A stationary toroidal magnetic field up to 320 gauss is applied.

The RF travelling field is generated by a transmission line of successive LC circuits which is set up on a half of the torus. Three types of the lines having different phase velocity of the travelling field are prepared: $V_p = 1.9 \times 10^6$ m/sec, $V_p = 1.0 \times 10^6$ m/sec and $V_p = 4.3 \times 10^5$ m/sec. The RF power, from 200 kW nominal output power oscillator, is fed to the line for a duration of 3.0 msec. The RF frequency is 3.0 MHz for the lines of $V_p = 1.9 \times 10^6$ m/sec, $V_p = 1.0 \times 10^6$ m/sec and 1.5 MHz for $V_p = 4.3 \times 10^5$ m/sec. The argon plasma is produced by the RF field itself; argon is used because it is easy to ionize.

We measure the loop resistance of the toroidal plasma by applying a weak pulse of induction field, which is generated by a current transformer with iron core (0.02 V.sec);

the loop voltage is 2 ∿ 3 volts. The induction field (a quarter period is 0.5 msec) is applied at 1.5 msec after the RF oscillator is turned on. In Fig.3, we show the time behavior of the toroidal plasma current and loop voltage with the pulsed perturbation field. We see that the current driven by the travelling field flows stationarily through the duration of RF excitation. The current response to the perturbation field indicates that the toroidal plasma is resistive. The plasma resistance is calculated from the loop voltage and induction current with a small correction due to loop inductance of toroidal plasma. We calculate the input power of the perturbation field; that is about 200 W. Because of this small power, we can not expect any remarkable modification of the plasma parameters by the application of induction field. Practically, such a modification was not found in an optical observation of the total light from the plasma. It is also observed that the resistance does not change so much during the RF discharge except the initial phase.

The RF power supplied to the line is measured by a directional coupler. The RF power absorbed by the plasma is estimated from the difference between the power supplied to the line and the power dissipated by a dummy resistor which terminates the transmission line. The plasma density is inferred from the fringes of 50 GHz microwave interferometer assuming a uniform density distribution. The generated current is measured by a Rogowski coil.

§4. Experimental Results and Discussions

The electron temperature estimated from Spitzer's conductivity is 2-4 eV assuming that the effective charge of ions Z is unity. The temperature measured by a Langmuir probe appears 6-13 eV.[6] Then the effective Z seems to be 4-6. In order to exclude this ambiguity of impurity effect, we calculate the electron collision frequency more directly from the relation $\nu_e = \eta \cdot \frac{ne^2}{m}$, where η is the resistivity obtained experimentally from the current response of perturbation field. The collision frequency ν_e ranges $2 \times 10^7 \sim 6 \times 10^7$ rad/sec, depending on the filling gas pressure. It is comparable with or higher than the applied RF frequency ($\omega = 1.9 \times 10^7$ rad/sec). Thus the plasma produced by the RF field is in the collisional regime. The electron-neutral collision frequency ν_{en} is lower than ν_{ei}; $\nu_{en} = 4.0 \times 10^6$ rad/sec at $P = 1.0 \times 10^{-3}$ torr and $T_e = 4$ eV. The collision frequency of ionizations is very small for the plasma of several eV. Thus we see that the main part of ν_e is the electron-ion collisions ν_{ei}.

We measure the generated current I_t, plasma density n, plasma resistance R and absorbed RF power P_a in such a plasma in order to study the relation (4). In Fig.4, we plot I_t, n, R and P_a as a function of the filling gas pressure P at a constant toroidal magnetic field $B_o = 128$ gauss. Here the transmission line of $V_p = 1.9 \times 10^6$ m/sec is used. The generated current I_t, shown in Fig.4(a), decreases with increasing P. If we describe, temporarily, the generated current by the safety factor q, it is 1.3 at $I_t = 250$ A,

B_o = 128 gauss. This q value evidently decreases with decreasing B_t. The plasma density increases with increasing P as shown in Fig.4(b). The plasma resistance increases slightly with increasing P as shown in Fig.4(c). The RF power absorbed by the plasma, shown in Fig.4(d), ranges 50-80 kW. The joule power dissipated by the DC current is calculated to be 2.5 kW at I_t = 250 A. Thus we see that it is a small part of the absorbed RF power. Similar dependences of the current and the RF power absorption on the pressure are obtained for the cases of $V_p = 1.0 \times 10^6$ m/sec and $V_p = 4.3 \times 10^5$ m/sec.

In the experiments, the RF travelling field produces ionization. The collision frequency ν_{ion} is small compared with electron-ion collision frequency. Therefore the ionization is believed to have no significant effect in resistivity. The ionization mainly affects the plasma parameters; the electron temperature is suppressed and the RF power absorption is enhanced.

In Fig.5, we replot from Fig. 4, the driving voltage P_a/I_o produced by the RF travelling field and the voltage $R \times I_t$ due to the frictional force as a function of P and hence ν_{ei} where $I_o = J_oS$ is the current in the case that all the electrons drift at V_p over the cross section S of the plasma column. The both voltages decrease with increasing P. The voltage P_a/I_o is proportional to and nearly equals to $R \times I_t$ within the range of $\nu_e = 2 \sim 6 \times 10^7$ rad/sec. This is the result expected from eq.(4).

The above result in Fig.5 is one at a lower magnetic field of 128 gauss. In a higher magnetic field of 320 gauss, we obtained a similar results, though there appears some difference.

The current is observed to increase with increasing the absorbed RF power P_a. In this case, however, the electromotive force does not increase so much, because the plasma density and hence I_o increases with P_a. Thus the increase in the current is mainly due to decrease in the resistivity.

Similar relations are also observed for the cases of $V_p = 1.0 \times 10^6$ m/sec and $V_p = 4.3 \times 10^5$ m/sec at $B_o = 128$ gauss. In Fig.6, we show the generated current I_t, voltages P_a/I_o and $R \times I_t$ as a function of V_p at a constant magnetic field and constant pressure. The current increases with decreasing V_p. The voltages P_a/I_o and $R \times I_t$ increase with decreasing V_p. This result can also be expected from the fluid model.

In the above treatments, we assume implicitly that the resistivity measured by a pulsed induction field plays the same role for the current driven by the RF travelling field. This assumption may be used in the case that both the current and the conductivity distribution have a considerably uniform profile. Therefore, the experimental results obtained above should be limited in this sense. Estimated correction factor is, however, thought to be smaller than two from the rough observation of current distribution. This smallness of the correction is due to rather uniform temperature profile which is accompanied with a poor plasma confinement.

§5. Conclusion

We describe the fluid model for the current generation by an RF travelling field and introduce an effective electromotive force p_a/J_o that plays a role of current driving electric field in a collisional plasma. Experiments were carried out in a collisional regime at a low toroidal magnetic field. The filling gas pressure was varied to change the collision frequency. We observed, for three different phase velocities V_p, that the current I_t is produced in such a way that P_a/I_o is nearly equal to $R \times I_t$, where R is the loop resistance of the toroidal plasma for the joule current and $I_o = -neV_pS$. Since P_a/I_o is the driving voltage and $R \times I_t$ is the voltage drop in the model, the experimental results may be summarized on the basis of voltage source model.

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Figure Captions

Fig.1. Qualitative picture for the force generation by RF travelling field in a collisional plasma. Here $\tilde{F}_z = -\tilde{J}_\theta \times \tilde{B}_r$.

Fig.2. Schematic diagram of synchromak device.

Fig.3. Time dependence of the generated current I_t and loop voltage U_{cr} with the pulsed induction field, where $B_o = 128$ gauss and $P = 4.5 \times 10^{-4}$ torr.

Fig.4. Generated current I_t, plasma density n, plasma resistance R and RF power P_a absorbed by the plasma for parameter of the filling gas pressure P, at a constant magnetic field $B_o = 128$ gauss.

Fig.5. Retarding voltage $R \times I_t$ and driving voltage P_a/I_o produced by the RF travelling field as a function of P at $B_o = 128$ gauss, where $I_o = J_oS$.

Fig.6. Dependence of the current I_t and voltages P_a/I_o, $R \times I_t$ on the phase velocity V_p at $B_o = 128$ gauss and $P = 6.0 \times 10^{-4}$ torr.

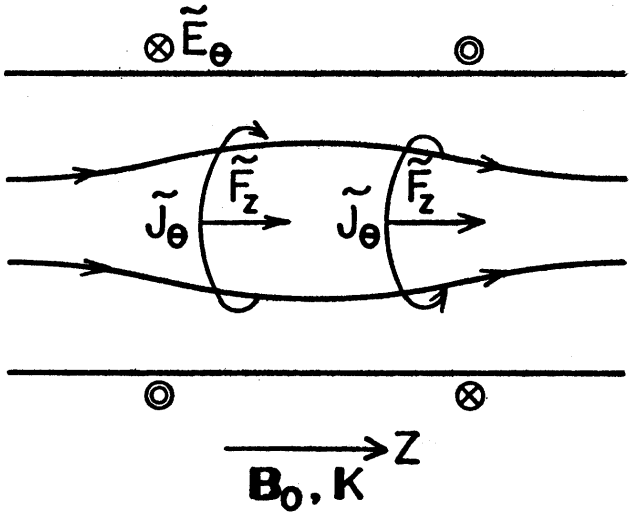

Fig.1. M.FUKUDA ⑥

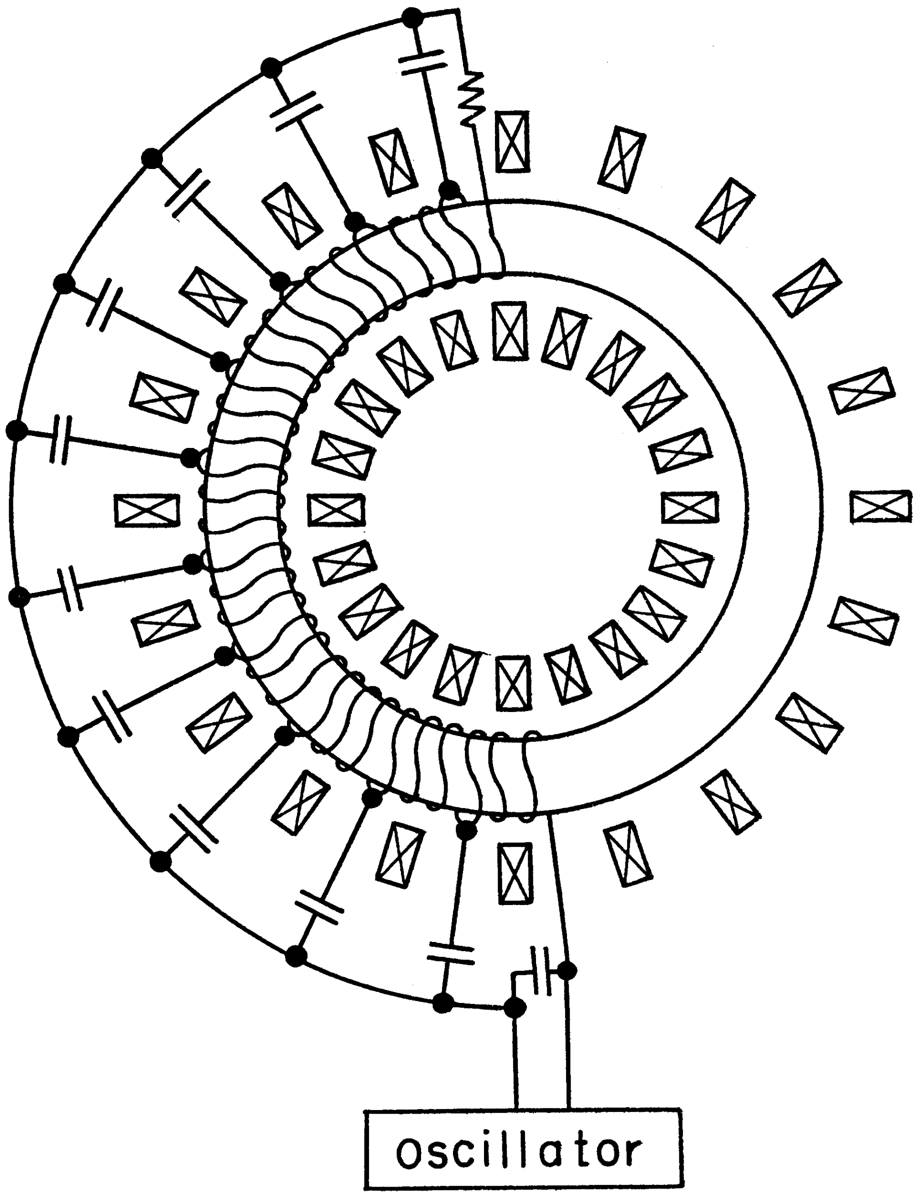

Fig.2. M.FUKUDA (6)

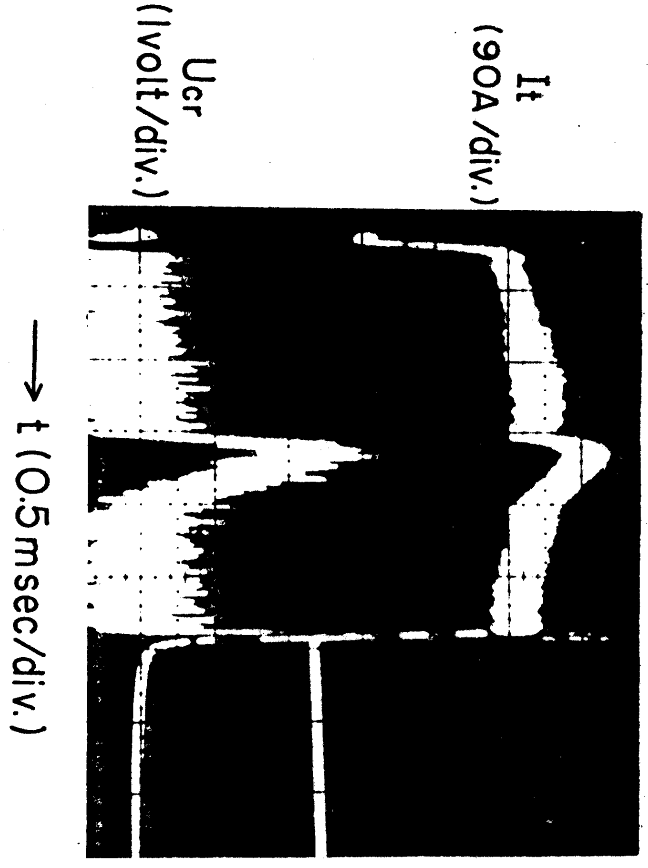

Fig.3. M.FUKUDA ⑥

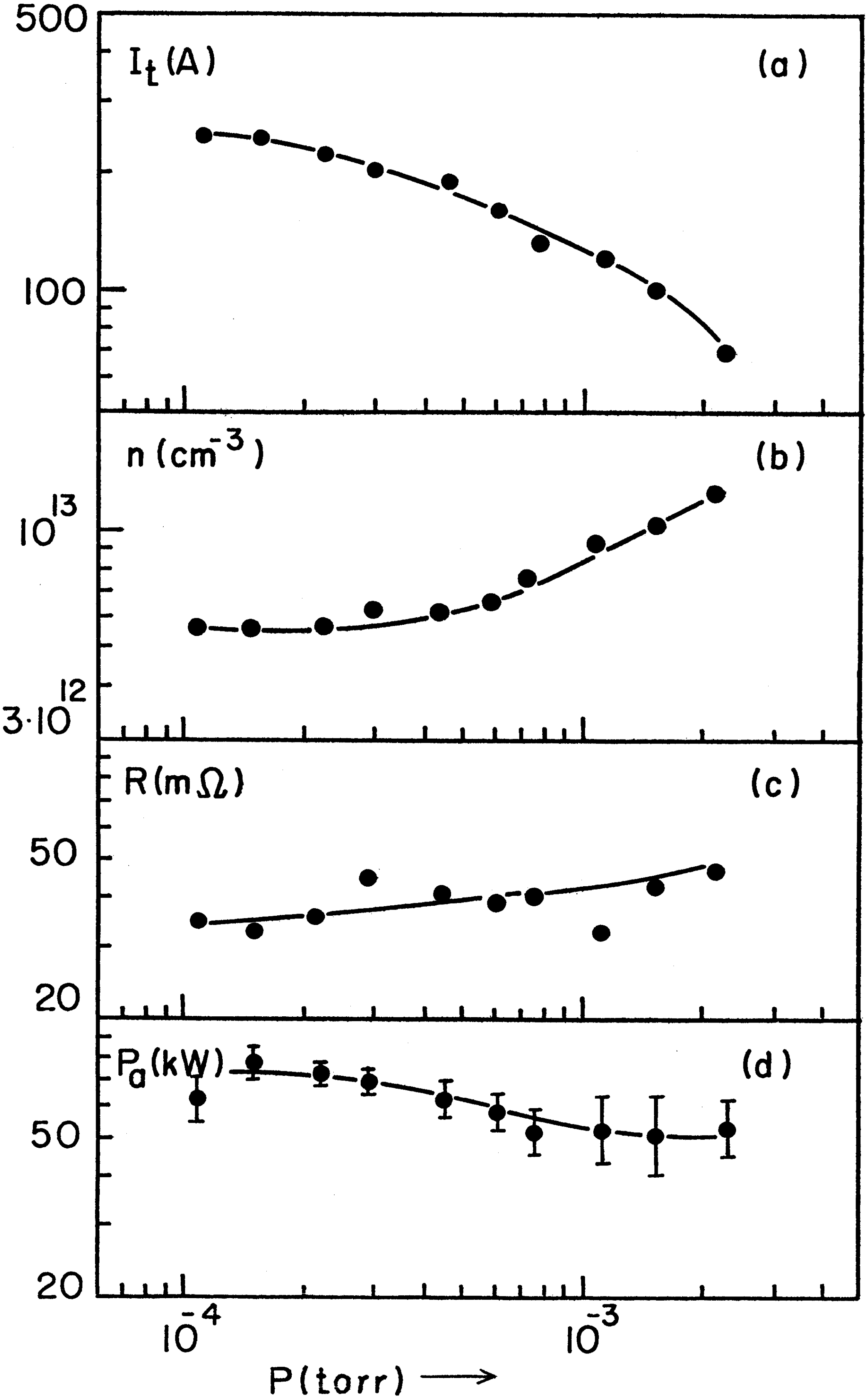

Fig.4. M.FUKUDA (6)

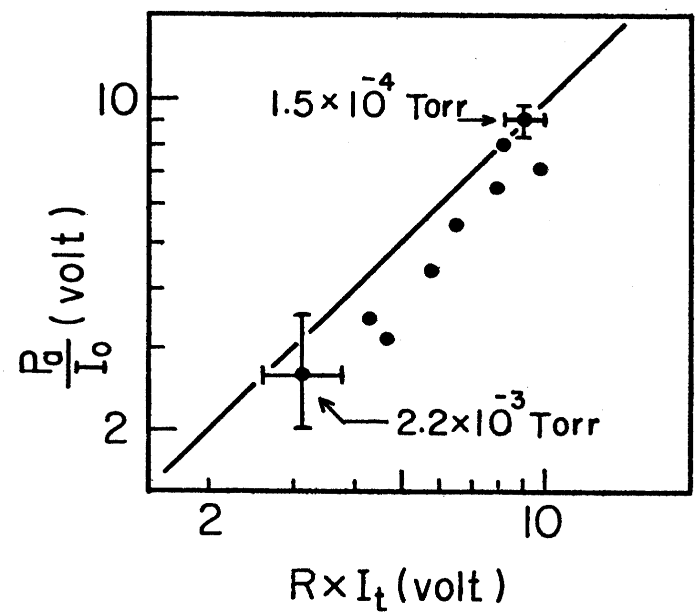

Fig. 5. M. FUKUDA ⑥

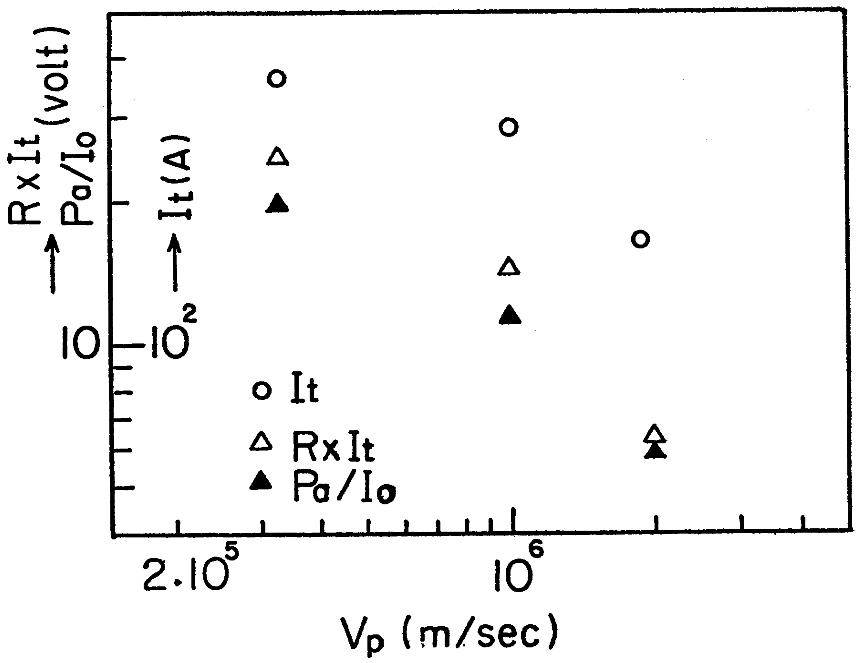

Fig.6.   M.FUKUDA   (6)