INSTITUTE OF PLASMA PHYSICS

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RESEARCH REPORT

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A Preliminary Experiment on Current Sustaining in a Magnetized Toroidal Plasma

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Abstract

It is experimentally shown that a traveling magnetic field along a torus induces d.c. toroidal current in a plasma. The circulating toroidal current changes sensitively when the toroidal magnetic field is applied. The results are explained by excitation of whistler waves. The maximum current achieved is about 180 A. It is found that electrons moving with the traveling wave are trapped in mirror or cusp regions formed by the traveling and the d.c. toroidal magnetic fields.

1. Introduction

Recently, much interests have been drawn for continuous operations of TOKAMAK apparatus. Because magnetic flux can not be increased infinitely, such an operation is impossible only by means of electromagnetic induction. Ohkawa[1] proposed the possibility to use high energetic ion beams to drive d.c. toroidal current. The other possibility is to use r.f. traveling electro-magnetic field. Historically, the first toroidal plasma experiment in the world done by Thoneman, Cowhig and Davenport[2] was to induce toroidal d.c. plasma current by traveling r.f. magnetic fields. They attained the current of 150 A using a 4 kW r.f. oscillator. The same sort of experiment had been carried out in U.S.S.R. on a much larger scale under the name of Delta project[3]. Although their aim was not to obtain toroidal d.c. plasma current, they observed the current of 2 kA. Nagao and Goto[4] also tried the similar kind of experiment. Unfortunately, in these previous experiments, little attention had been paid to operate under the influence of toroidal magnetic field. Recently, Wort[5] suggested the possibility of sustaining the toroidal current in TOKAMAK with r.f. traveling magnetic fields and calculated neccessary r.f. power for the TOKAMAK fusion reactor proposed by Golovin et al.[6]. Under these circumstances, it will be worth while to study the influence of a toroidal magnetic field on d.c. plasma current driven by an r.f. traveling magnetic field. Here is described a preliminary experiment to learn the effect of toroidal magnetic field on d.c. toroidal current using the helical transmission line system similar to Thoneman's. In the following sections, our experimental apparatus and observed results are described. In the final sections, discussions are presented for further experiments.

2. Experimental Apparatus

A transmission line is arranged around the glass of 24 cm major diameter and 6 cm minor diameter as shown in Fig. 1. The whole view of the apparatus can be seen in Fig. 2. The coil of the transmission line is a copper tube (2.5 mm in diameter) through which cooling water is running. To form the transmission line, the coil is subdivided into 16 sections, each of which has 8 turns and is loaded with a capacitor of 1000 pF. The phase velocity of the transmission line is designed to be 6.7×10^5 m/sec and the characteristic impedance becomes 69 Ω. As is known, these quantities are independent of the frequency of a traveling wave. The transmission line can be either short circuited or terminated in its characteristic impedance. Even in the case when the transmission line is short circuited, component of traveling wave appears as a result of power input into a plasma. The input end of the line is fed from a 2.68 MHz oscillator capable of delivering 10 kW nominal r.f. power. The output power of the oscillator can be blocked easily by making small change of the circuit. Here, the frequency of the oscillator is adjusted so that three wave lengths of the traveling wave become the circumference of the torus. Under this condition, the product $\tilde{E}_\theta \cdot \tilde{B}_r$ which is proportional to the electro-motive force of the circulating current around the torus is nearly maximized, where $\tilde{E}_\theta$ is the azimuthally induced r.f. electric field and $\tilde{B}_r$ is the radial component of the traveling magnetic field.

Copper tubes of 32 turns with water cooling are so arranged to produce the toroidal magnetic field of 150 Gauss on the minor axis of the torus when current of 300 A is fed from a D.C. current source. Here, argon gas is leaked through a needle valve into the toroidal tube for a working gas. The gas pressure is measured by a Schulz type ionization gauge. The time duration of a discharge is limited by over heating of the glass ware due to the plasma bombardment.

3. Measurement and Results

3.1. Formation of a traveling r.f. field

Formation of a traveling r.f. field is observed from a measurement of r.f. voltage $\tilde{V}_c$ across the capacitors of the transmission line. In the case that the end of the line is short circuited, only standing wave appears when there is no plasma. The apparent irregular form of the standing wave seen in Fig. 3 is mainly due to the fact that one wave length does not contain definite number of sections of the transmission line. The plasma changes the above situation largely. The wave becomes traveling one because of heavy loading by the plasma.

3.2. Power input to the plasma

Figure 4 shows the voltage and the current wave forms at the feed point of the transmission line. The current wave form is measured with an usual pick up coil, and the voltage wave form is obtained with a capacitance divider. The phase difference without plasma between the voltage and the current is very close to $\pi/2$, which means that the power flow into the transmission line is very small. However, the phase difference becomes very small when the plasma is produced. In this case, the power flow into the plasma is estimated to be several kW. The observed current wave form is considerably deformed from the sinusoidal one especially when the toroidal magnetic field is applied.

3.3. Spatial distribution of r.f. field in the plasma

Spatial r.f. field distributions are measured by a small pick up coil cased in quarts tube of 8 mm in diameter. Figure 5 shows the toroidal component of r.f. magnetic field $\tilde{B}_z$ on the meridian plane of the torus. It is noted that the field distribution without plasma closely coincide with the theoretical 1/r dependence. In our case, the plasma does not shield the r.f. field so completely as in the case of Borzunov[3] et al. It is worth while to note that when B_t is applied, the r.f. field penetrates into plasma.

3.4. Circulating d.c. current

Circulating d.c. current I_t is estimated from the poloidal component of related magnetic field, which is measured by a small Hall element placed just outside the discharge tube. Figure 6 shows the dependence of I_t on the operating gas pressure p and B_t. It is seen that I_t has a peak at a certain value of B_t for a given gas pressure. In the case that B_t is zero, I_t increases as p decreases, but possible lower limit of p is existing, since break down of the gas becomes defficult below the pressure of 9×10^{-4} torr. The d.c. voltage V_p which is supplied to the oscillator tube is also changed. The result is presented in Fig. 7. It is seen that I_t rises at around 6 kV and increases very sharply with V_p. The distribution of I_t on the meridian plane of the torus can easily be deduced from the measured profiles of poloidal magnetic field B_θ. To obtain B_θ profile, a small Hall element in a quartz tube is scanned on the meridian plane. Typical profiles are shown in Fig. 8. It is seen that the center of I_t channel shifts outward from the minor axis of the glass ware. This is understood from the fact that any toroidal current loop receives expanding force by its own magnetic field. As the slope of B_θ over radius is constant in this case, fairly flat distribution of I_t is formed. Since the Hall element flux meter used here is lack of time response, only time integrated d.c. component of I_t is observable. Using a small pick-up loop placed just outside the glass ware, time varying wave form of I_t is measured. As shown in Fig. 9, a remarkable difference is seen between the cases $B_t = 0$ and $B_t = 53$ Gauss. In the case $B_t = 0$, the frequency of I_t is twice as much as that of the traveling wave, while, in the case $B_t = 53$ Gauss, the frequency of I_t becomes equal to that of traveling wave. In order to check if I_t has true d.c. component, amplitude of the traveling wave is heavily modulated by a slight re-arrangement of the oscillator. The response of I_t to the modulation is observed by the same pick-up loop. A typical example is presented in Fig. 10. An evidence of build up of d.c. component is found in the wave form in the figure.

3.5. Plasma density and electron temperature

Plasma density and electron temperature are measured by a Langmuir probe of co-axial form, of which the outer cylindrical reference electrode is made of tantalum. In order to avoid induction of r.f. field, the bias potential of the probe is carefully supplied from batteries floated from the earth potential. Here, plasma density is estimated from ion saturation current. A plasma density distribution on the meridian plane is shown in Fig. 11. In this case the degree of ionization becomes little less than 10 %. The electron temperature of the plasma is obtained by the same probe. It is 7.5 eV on the minor axis and 4 eV at the periphery of the plasma.

4. Discussions and Conclusions

It is clarified experimentally that circulating d.c. current I_t around the torus is observed even under the presence of toroidal magnetic field B_t. The motive force to drive electrons along the minor axis with the traveling wave is proportional to the dynamo-force $\tilde{I}_\theta \cdot \tilde{B}_r$, where $\tilde{I}_\theta$ is induced poloidal current. Since $\tilde{I}_\theta$ is propotional to the conductivity of the plasma, I_t is also a function of the conductivity. It is well known that the conductivity perpendicular to a magnetic field is proportional to $(\nu/\omega_c)^2$ as far as the classical theory concerns. In our usual experimental conditions, in which p is 3×10^{-3} torr and B_t is 100 gausses, ν/ω_c is much less than 1/10. Therefore, the toroidal magnetic field of only 150 Gauss reduces the conductivity more than two order of magnitudes. Such a decrease of the conductivity should also lead to a decrease of I_t. Figure 6, however, shows that such a simple model is not hold in this case. The d.c. current has a peak at a certain value of the toroidal magnetic field B_t, and the field, at which the peak appears, shifts toward higher side as the gas pressure increases. This dependence of I_t can be explained in connection with the excitation of whistler waves. The dispersion relation of whistler waves is given by

$$N^2 \simeq 1 - \frac{\Pi^2}{(1 - \frac{\Omega_e}{\omega}\cos\theta)\omega^2} , \qquad (1)$$

where N is the reflective index, Ω_e the electron cyclotron frequency, θ the angle of wave propagation to the magnetic field, and Π the plasma frequency. The perpendicular component of the wave number $k_\perp$ is determined by the boundary condition,

$$J_o(k_\perp r_p) \simeq 0,$$

for the lowest radial mode, where r_p is the radius of plasma and J_o is

Bessel function of zeroth order. In this experimental condition where $r_p = 2.5$ cm, the dispersion relation (1) leads to the following simple relation for $\frac{\Omega_e}{\omega}\cos\theta \gg 1$,

$$B_{tw} \simeq 2.3 \times 10^{-11} n\alpha \text{ (gausses)}. \qquad (2)$$

Where B_{tw} is the magnetic field at which whistler waves can propagate and n is the electron density in cm^{-3}. The α is the correction factor for the doppler shift arising from the drift motion of the electrons by the presence of the traveling wave and is given by

$$\alpha = 1 - \frac{I_t}{\pi r_p^{\,2} e n V_p} .$$

In the experiments, the minimum value of α is about 0.8. In the case $n = 5 \times 10^{12}$ cm^{-3} and $\alpha = 0.9$, magnetic field B_{tw} becomes about 100 gausses which agrees fairly well with the observed value. The width of the observed peak of I_t should depend on the ratio of the collision frequency of electrons to the r.f. frequency. The ratio is of the order of unity, so that observed rather clear peaks suggest that there are some additional mechanisms related to the wave excitation. The penetration of the r.f. field in the case $B_t = B_{tw}$ may be promoted by the excitation of the wave. Compressional Alfvén wave, which appears at much higher B_t, belongs to the same branch as whistler mode. Therefore, it is said that the physical situation similar to the one proposed by Wort is realized in this experiment.

It is supposed from the physical situation of the experiment that electrons should have some bunching structure. The observation of B_θ induced by I_t is suggesting that some of the electrons of the plasma are trapped by the traveling wave and circulating around the torus. When B_t is zero, the frequency of B_θ is twice as much as that of the traveling wave. This indicates that two groups of electrons exist in each wave length of the traveling wave. Taking the phase relation into account, electrons are considered to be trapped in the two cusp regions formed along a wave length of the traveling wave. In the case a certain value of B_t is applied, however, only one group of electrons in each wave length is expected, since two cusp regions turn into one mirror region. In fact, the frequency of B_θ changes into the same one as that of the traveling wave, when B_t is applied. It is very important to know whether I_t is carried by completely bunched electrons or not. The build up of true d.c. component of I_t is observed by blocking the output power of the oscillator.

It is of course, that the grow up of the d.c. component is due to the collisional momentum transfer to the field electrons from the bunched one. The radial distribution of I_t is measured. The results show some evidence of the toroidal outward drift of the current channel. The same tendency is found on the density distribution. It should be noted that plasma becomes denser with B_t. This may be due to improved confinement of electrons. The power input rate to the plasma is estimated to be 4 to 6 kW. The most of the power is consumed for ionizing the working gas. In the future experiment, it is desirable to use some other ionization and plasma heating techniques, for instance, such as inductive Joule heating. It is clear that much higher toroidal field will become necessary.

Acknowledgement

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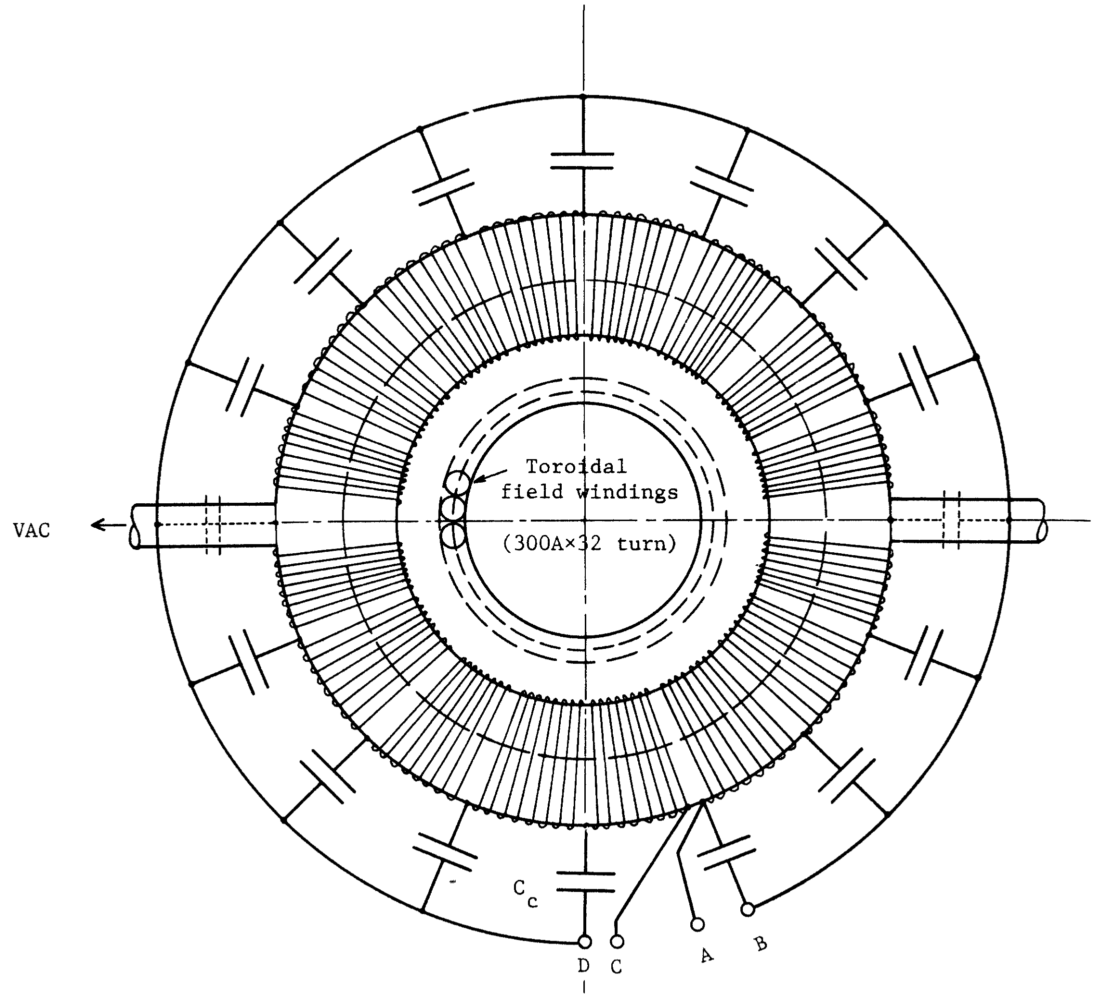


Fig. 1 Schematic drawing of the experimental apparatus. Discharge tube: major diameter = 24 cm, minor diameter = 6 cm, transmission line: composed of 16 sections. Each section consists of an r.f. coil of 8 turns and a ceramic capacitor of 1000 pF. A and B are the feeding points of the r.f. power, and C and D are the end points of the transmission line, which are shorted or loaded with a resistor of 50 Ω.

(a)

(b)

Fig. 2 Photographs of the experimental apparatus.
a) a whole view of the apparatus, b) a closing up of the transmission line.

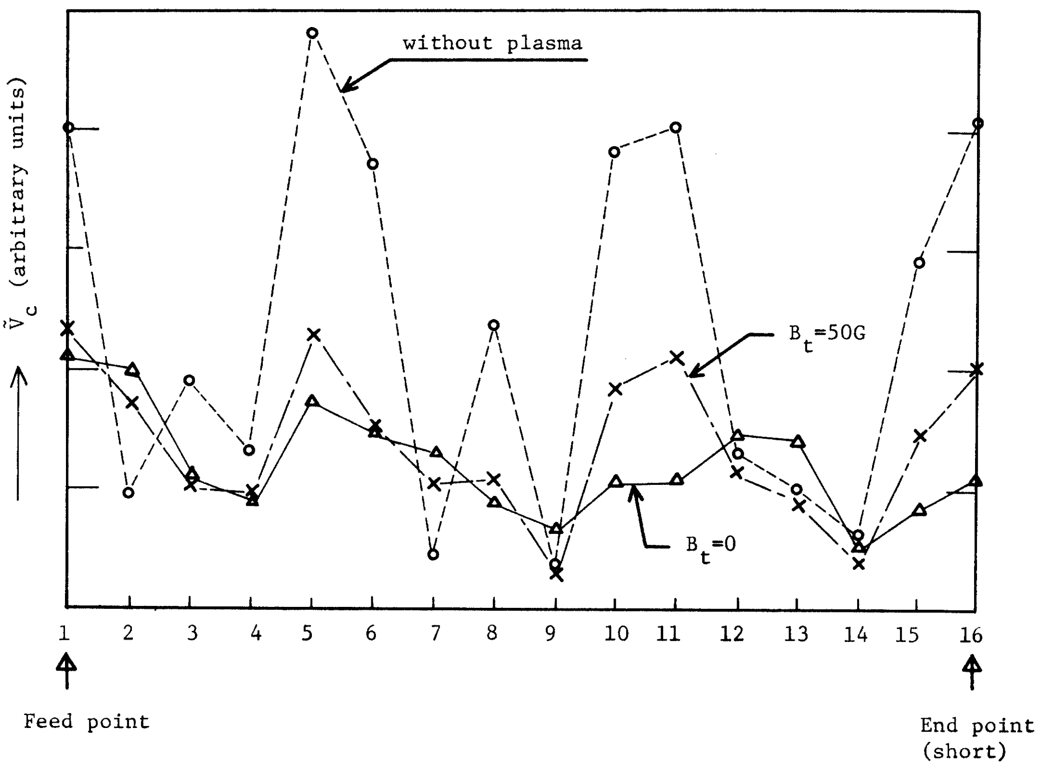
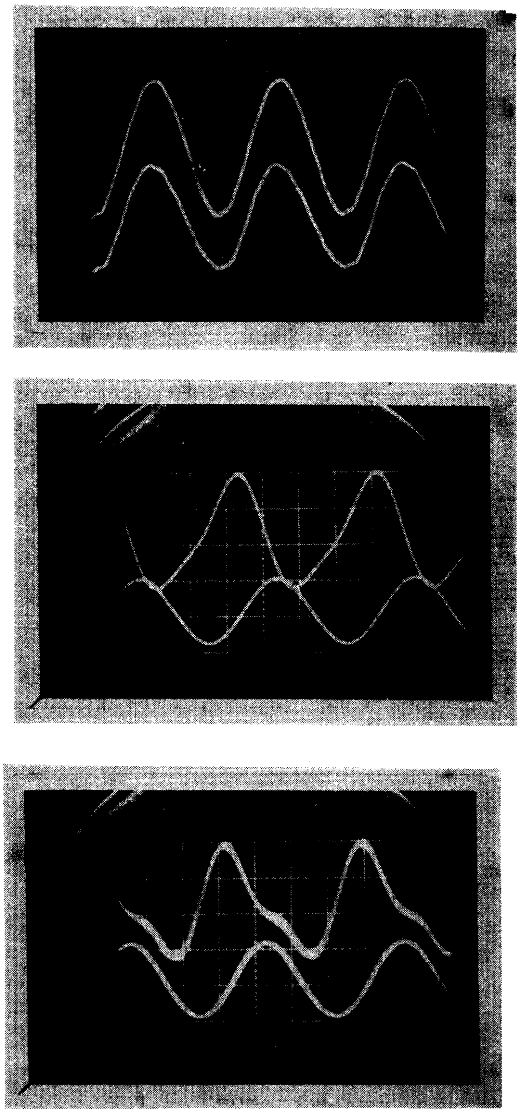


Fig. 3 Distribution of r.f. voltages $\tilde{V}_c$ across the capacitors along the minor axis of the torus. In this case, the end of the transmission line is short circuited. The voltage standing wave ratio can be estimated roughly.



(a)

(b)

(c)

Fig. 4 Wave forms of the r.f. voltage and the current at the feed point of the transmission line. The current is measured by a small pick up coil and the wave form shown is its time delivative. The D.C. voltage V_p applied at the anode of the oscillator is kept constant to be 10 kV. Upper traces: current wave form, 1 kV/div., scanning speed: 0.1 μsec/div. a) in the case without plasma; the phase difference between the voltage and the current is close to $\pi/2$, which means the power flow into the transmission line is very small. b) $B_t = 0$, $p = 2.8 \times 10^{-3}$ torr, $I_t = 30$ A; power flow ~ 3.5 kW. c) $B_t = 53$ gauss, $p = 1.4 \times 10^{-3}$ torr, $I_t = 40$ A; power flow ~ 5 kW.

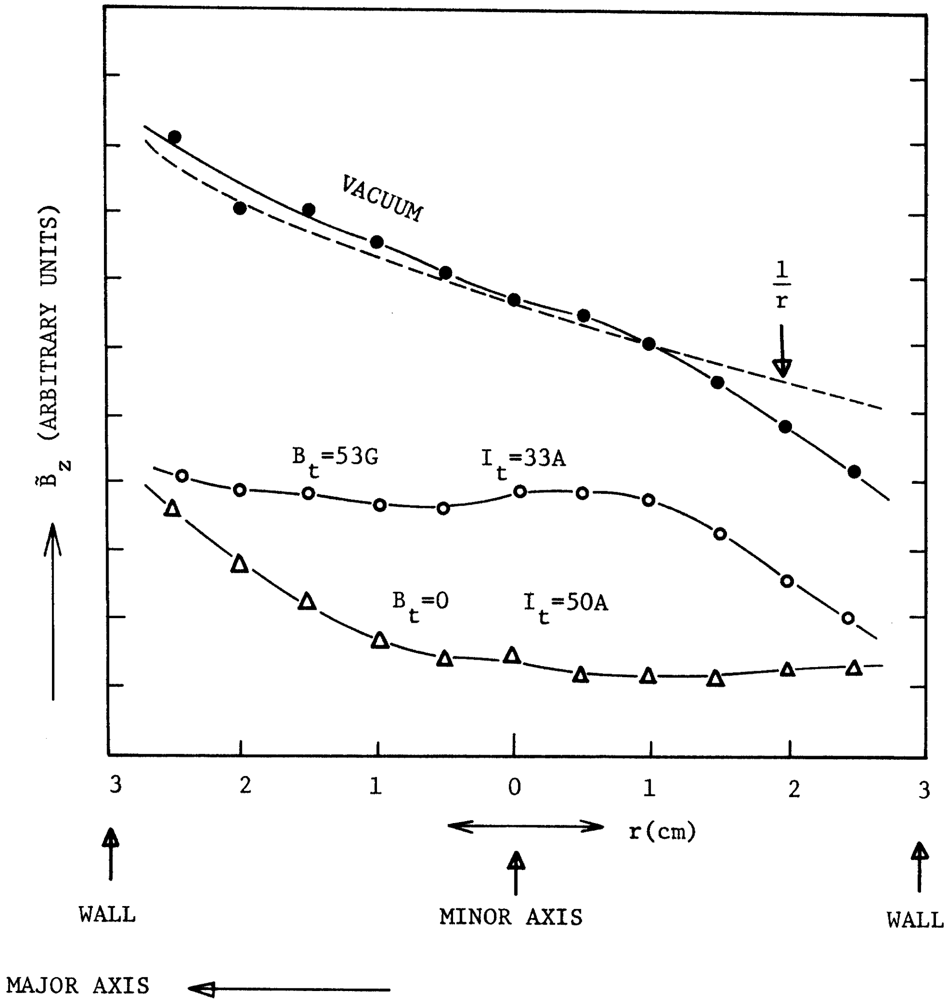


Fig. 5 Spatial distributions of $\tilde{B}_z$ on the meridian plane of the torus. $p = 3 \times 10^{-3}$ torr, V_p = 10 kV.

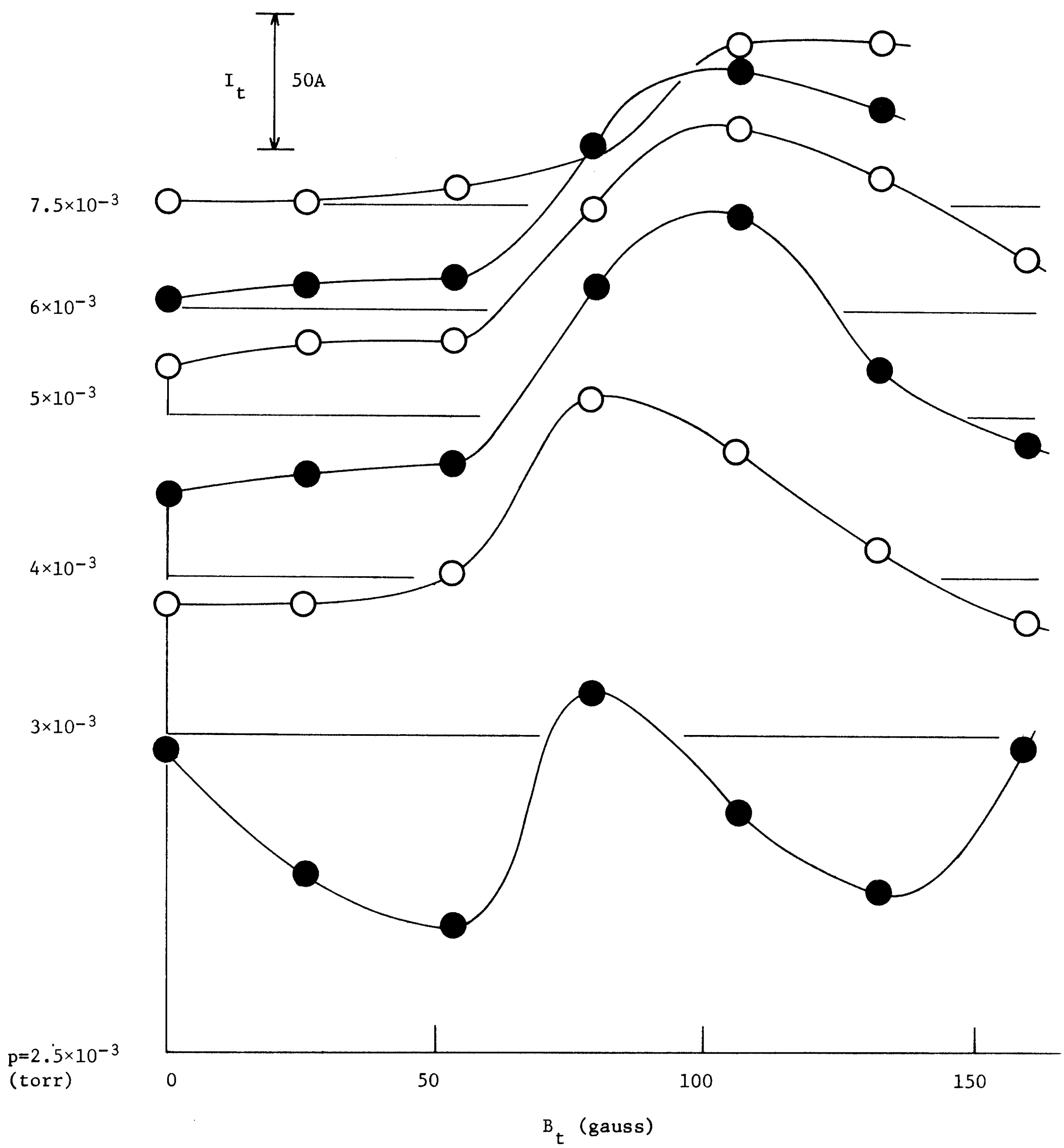


Fig. 6 Variation of I_t with the gas pressure p and the toroidal field B_t.

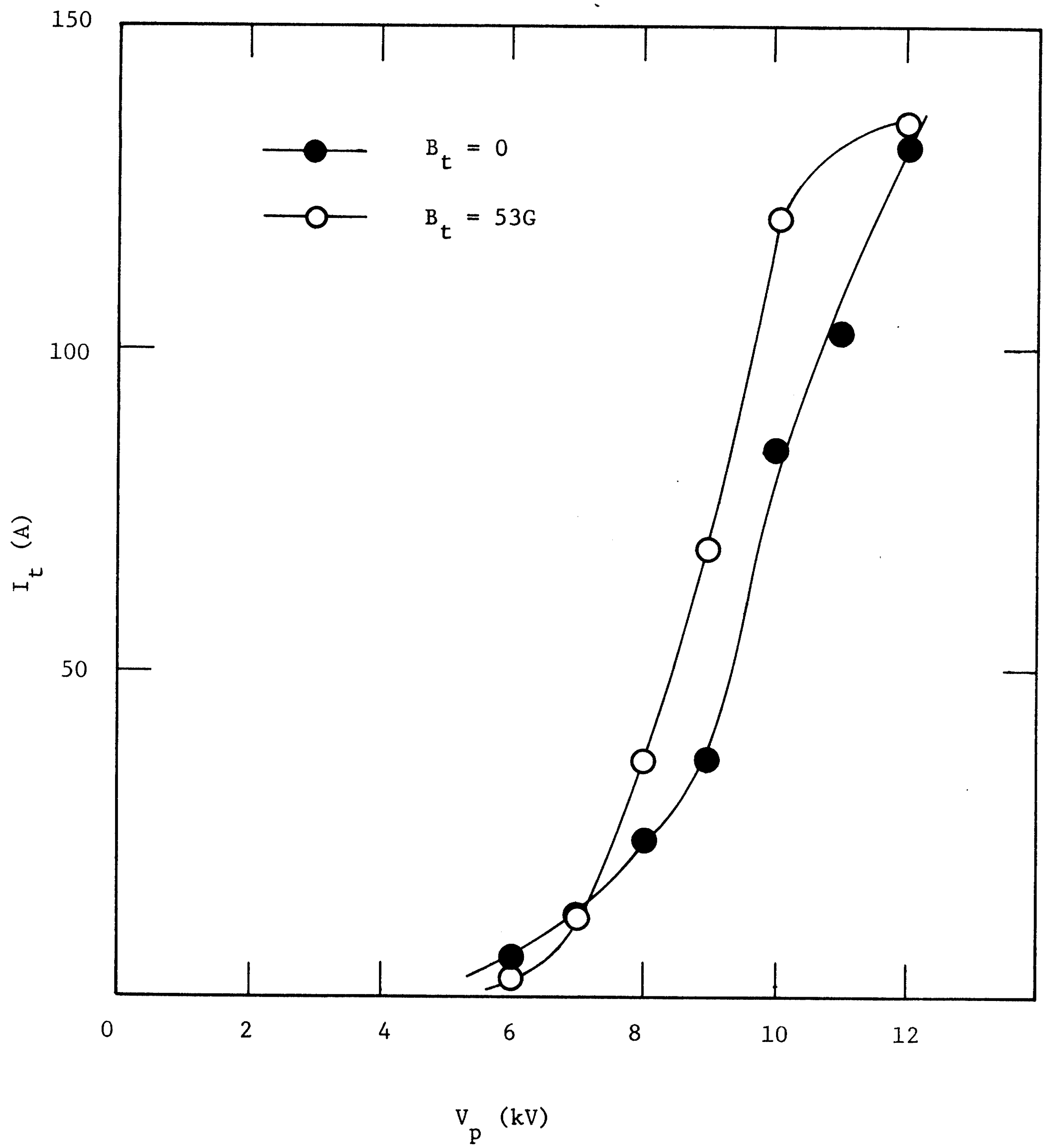


Fig. 7 I_t as a function of V_p, where $p = 3 \times 10^{-3}$ torr.

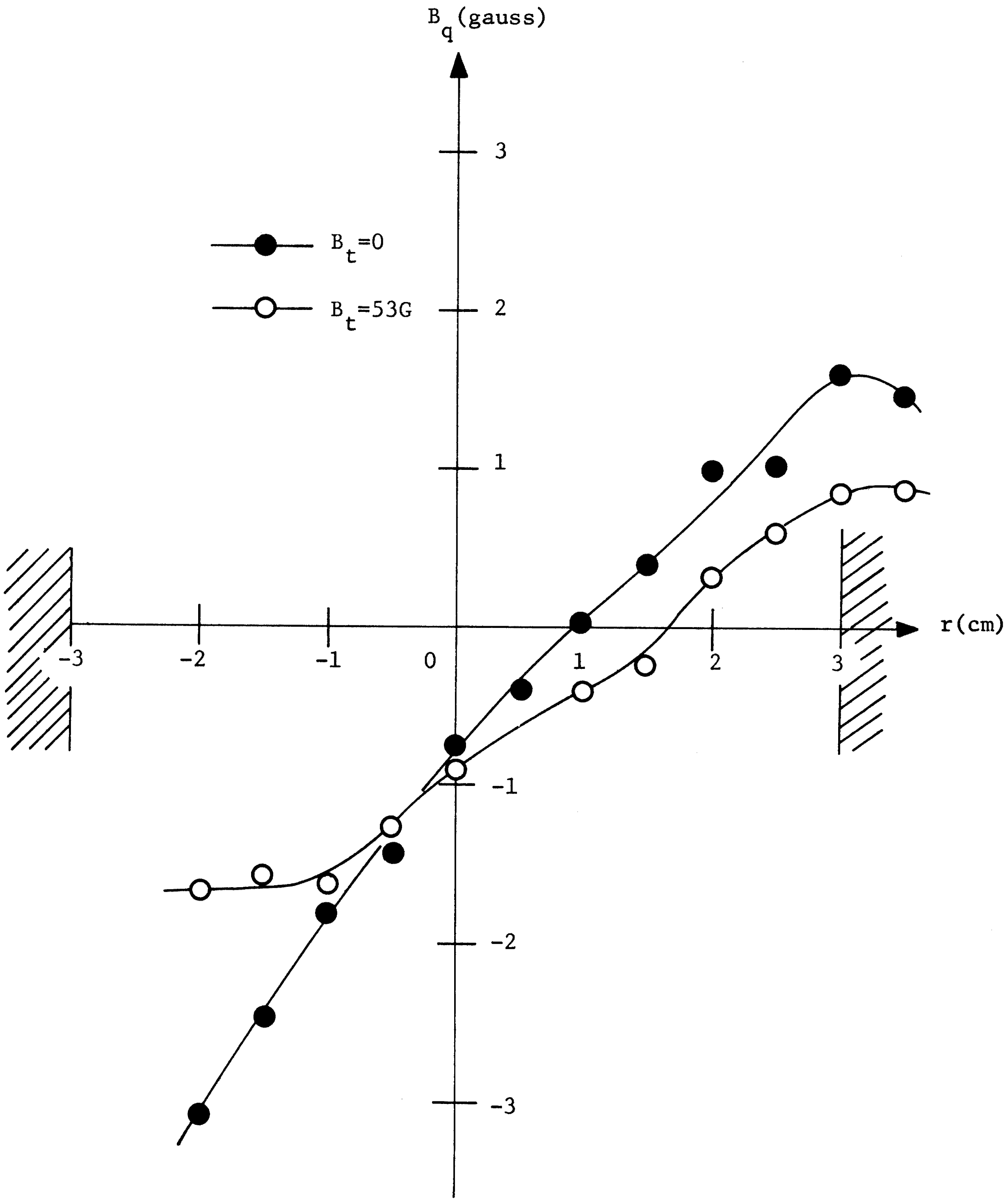
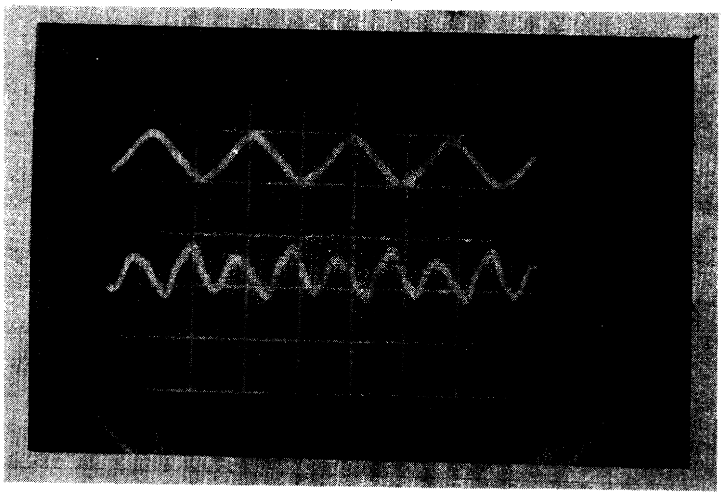
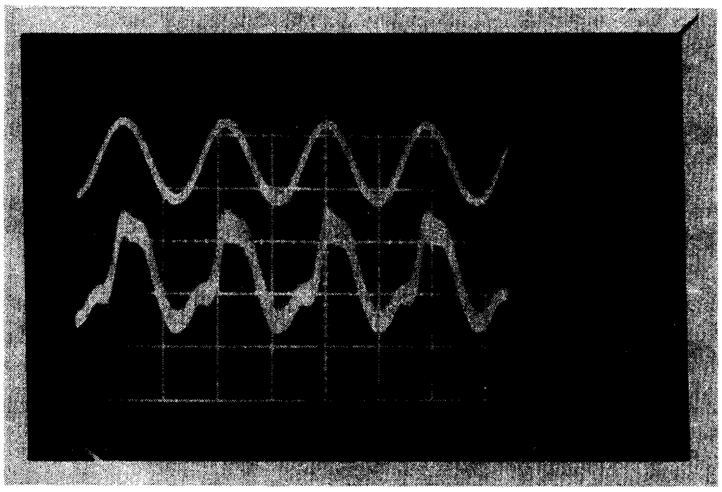


Fig. 8 Spatial distributions of B_θ on the meridian plane of the torus. $p = 3 \times 10^{-3}$ torr, $V_p = 10$ kV.



(a)



(b)

Fig. 9 Alternating component of B_θ due to the plasma current. The axial field component $\tilde{B}_z$ outside the r.f. coil is also shown at the upper trace. Magnetic probes for B_θ and B_z are set up on a plane formed with the major axis and a major radius. Upper traces: $\partial B_z/\partial t$, lower traces: $\partial B_\theta/\partial t$, scanning speed: 0.2 μsec/div. a) $B_t = 0$, b) $B_t = 80$ gauss.

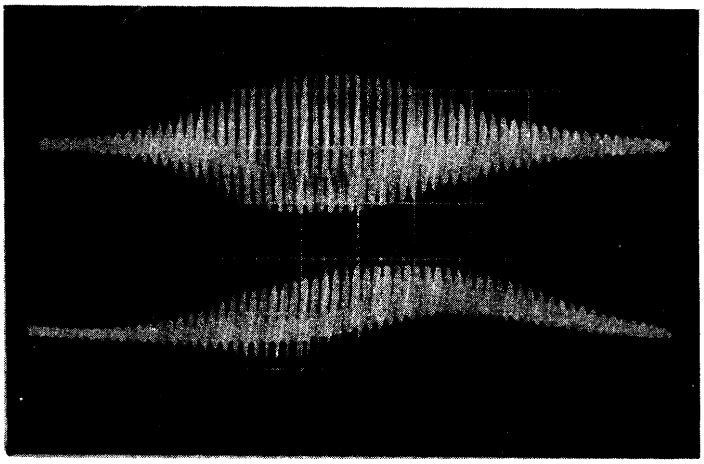


Fig. 10 Time dependence of the axial plasma current when the traveling wave is blocked. Upper trace: wave form of the blocking oscillation, lower trace: B_θ obtained from the time integration of $\partial B_\theta/\partial t$, scanning speed: 20 μsec/div.

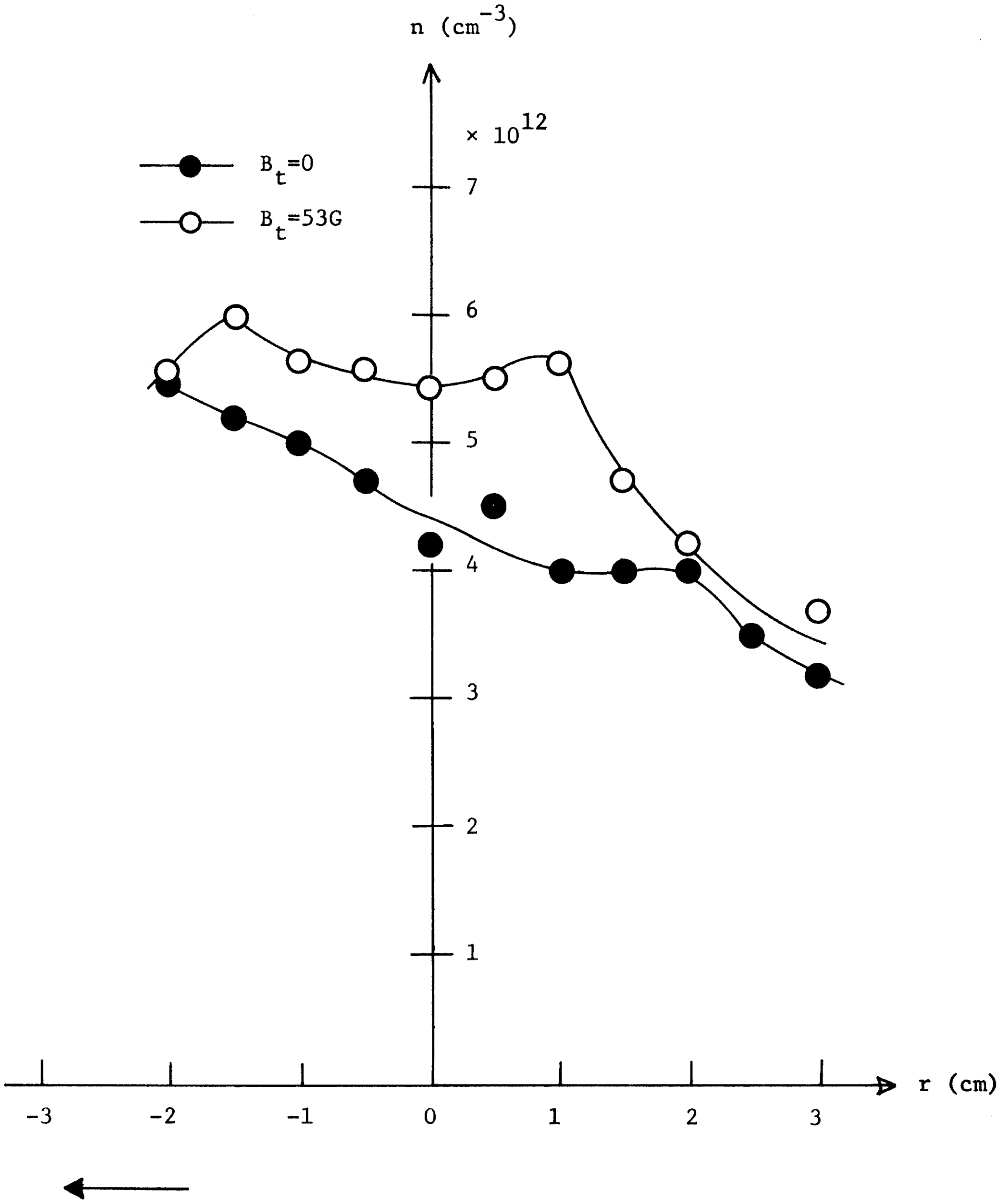


Fig. 11 Plasma density profiles on the meridian plane of the torus. $p = 3 \times 10^{-3}$ torr, V_p = 10 kV.