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COUPLING TO FAST WAVES VIA A PHASED LOOP ANTENNA ARRAY FOR FAST WAVE CURRENT DRIVE IN THE JFT-2M TOKAMAK

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A phased loop antenna array was employed to launch fast waves into a plasma in which the frequency is of the order of 10 ω_{ci}. A high loading resistance of about 5 Ω was obtained and its value agrees well with the theoretical estimation. The loading efficiency of about 80% was obtained at a frequency of 200 MHz. The travelling fast waves were excited by phase control of the two loop antennas array and the excitation of the waves like coaxial mode was observed at in-phase feeding of two loop antennas. Use of the fast wave for steady state current drive was suggested.

Keywords : Fast Wave Current Drive, Phased Loop Antenna Array, JFT-2M Tokamak, Loading Resistance, Coaxial Mode

JFT－2Mトカマクにおける速波電流駆動用ループアンテナの結合特性

日本原子力研究所那珂研究所核融合研究部
上杉喜彦・山本　巧・大塚英男・菊地一夫

（1986年6月25日受理）

位相列ループアンテナが，約10倍オーダーのイオンサイクロトロン周波数領域の速波をプラズマ中に励起するために用いられた。ループアンテナを用いることにより，プラズマ負荷抵抗は，200 MHzにおいて約5 Ωの高い値が得られ，理論計算値ともよく一致した。ループアンテナの結合効率は約80％である。2ループアンテナの位相制御により進行波が励起され，電流駆動への適用の可能性が示された。また，同相給電の場合同軸モードと思われる波の励起が観測された。

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Contents

目　　次

1. Introduction

A radio frequency current drive is one of the most effective methods to realize a steady state operation of tokamak plasmas. Current drive by lower hybrid waves (LHW) has a high efficiecny and is easy for access to the plasma using a waveguide array [1] - [3]. However, the efficiency decreases rapidly with increasing the density and no rf current is induced beyond the density limit [4].

The electrostatic slow waves such as LHW interact strongly with plasmas through Landau damping in high density and high temperature region. The accessibility of LHW to the center of hot reactor-like plasma is poor since the wave power would be absorbed near the plasma surface. The fast electromagnetic waves can propagate to higher density region beyond the LH resonance layer [5]. Also, fast waves are less affected with non linear effects, such as parametric decay instabilities than slow waves since the fast waves have relatively long wavelength perpendicular to the magnetic field compared with the slow waves and does not propagate in resonance cones. The fast wave current drive (FWCD) is based on the same mechanism as LH current drive that the current carrying electrons are accelerate through Landau damping [6] - [7]. Although Landau damping of the fast waves is weak in low temperature plasma, a production of the high energy electron tail or several KeV plasma can increase the absorption of the fast waves in plasma. For these reasons, fast waves have a capability to drive the plasma current in high density and hot plasmas.

2. Phased loop antenna array and RF system

In order to excite fast waves in plasma, slow wave structures like phased waveguide array [8] - [9] or phased loop antenna array are required. In our experiments, a phased loop antenna array was used because of its high power capability. The schematic view of the three loop antennas array installed at the midplane of the torus is shown in Fig. 1. It has same configuration as those commonly used for fast wave ion cyclotron heating in tokamaks. Single layer Faraday shields cover each loop antenna to suppress the parallel electric field which couples with the slow waves, and to obtain good coupling of fast waves with plasma. Particle shields made of carbon graphite are located on the side of Faraday shields. The frequency of the rf power fed to the loop antenna must be selected by

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3. Coupling experiment

The coupling experiments were carried out in the JFT-2M tokamak. JFT-2M is a non circular tokamak [10]. The major and minor radii are 1.31 m and 0.55 m × 0.35 m, respectively. The typical parameters of ohmic plasma are the toroidal magnetic field, $B_t \leq 1.43$ T, the plasma current, $I_p \leq 500$ kA, the electron density, $n_e \leq 6 \times 10^{19}$ m^{-3} and the electron temperature, $T_e \leq 1$ keV. The power spectra of the waves excited by two loop antennas array are shown in Fig. 3, taking the phasing between them as a parameter. When the gap between two antennas is 20 cm and $\Delta\phi = 90°$, the spectrum has a peak near $N_z = 2.5$. This peak in the spectrum moves to $N_z = 4$ when the antenna gap is 10 cm. The power spectra of the excited waves can be changed by means of selecting two loop antennas among three loops.

The cutoff density for the fast waves is given approximately by

$$\omega_{pe}{}^2(\text{cutoff}) = \omega\omega_{ce}(N_z{}^2 + N_\theta{}^2 - 1)^{1/2}(N_z{}^2 - 1)^{1/2}, \qquad (1)$$

where ω_{pe} and ω_{ce} are the electron plasma frequency at the cutoff layer and the electron cyclotron frequecny, and N_θ is the poloidal refractive index. The cutoff condition determines a lower limit on the density where the fast waves can propagate and the accessibility condition that $N_z > 1 + \omega_{pe}{}^2/\omega_{ce}{}^2$ $(\omega = \omega_{LH})$ gives an upper limit on the density. From these two conditions, the density region accessible for the fast waves taking account of coupling between plasma and loop antenna, and the damping of fast waves in plasma. A high rf power at a frequency of 200 MHz can be amplified by commercially available tubes and its long wavelength of 1.5 m is preferable to the loop antenna excitation. The absorption efficiency by Landau damping increases with frequency and the coupling efficiency of the loop antenna with fast waves also depends on frequency. A frequency of 200 MHz which corresponds to (10-15)ω_{ci} of the hydrogen plasma is most suitable in JFT-2M. The rf system of FWCD is shown in Fig. 2. It has three amplification stages. The final tube, TH-116 generates 100 kW with a duration of 100 msec. The rf power of 100 kW is divided into two lines by a 3 dB hybrid coupler. The phase difference between them is controlled by a line stretcher. The impedance matching of each line is tuned by $\lambda/8$ double stub tuners.

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The loading resistance of the loop antennas was obtained from the measurements of the reflection coefficient of them, and from the impedance matching between the loop antennas and 50 Ω transmission lines using $\lambda/8$ stub tuners. The time evolution of the reflection power in the presence of the plasma is shown in Fig. 5. The rf power of about 1 kW was fed continuously to a single antenna. The reflection power decreases from its vacuum level as soon as the electron density rises and does not depend on the electron density. However, it depends on the horizontal position of the plasma column as shown in the figure. When the plasma moves apart from the loop antenna, the reflection power increases. From these observations, it can be shown that the loading of the loop antenna depends on the density at the peripheral region near the antenna, not on the mean density as already shown in ICRF experiments. The loading resistance obtained from the reflection measurements is shown in Fig. 6 as a function of the frequency. The resistance calculated with the coupling code of the loop antenna [11] is also shown in the figure. The experimental values agree well with the theoretical one. A relatively high loading resistance of 4.5 Ω was obtained when f = 200 MHz. The peak near f = 200 MHz should be related with $\lambda/4$ resonance of the loop antenna. The impedance matching with stub tuners gives the loading resistance, Z_{RV} = 1.2 - 2 Ω in vacuum and Z_{RP} = 5 - 8 Ω in plasma when the rf power is up to 10 kW. The region of the exact impedance matching in vacuum is very narrow since the mutual coupling between two loop antennas is strong. In the presence of the plasma, the coupling to fast waves makes the mutual coupling weak. The loading efficiency defined by $\eta_1 = (Z_{RP} - Z_{RV})/Z_{RP}$, as high as 80% can be achieved. The loading resistance Z_R in Fig. 6 corresponds to $Z_{RP} - Z_{RV}$. The VSWR of the loop antenna as low as 10 makes it possible to launch the rf power of about 200 kW from the loop antenna through WX-77D coaxial line in the absence of SF_6 pressurization.

The theoretical estimation gives Z_R and η_2 as a function of $\Delta\phi$ in Fig. 7, where η_2 is defined by the ratio of the radiated power integrated over $|N_Z| > 1$ to the total radiated power. The excited waves with $|N_Z| < 1$ can not penetrate into the plasma and do not contribute to the current

drive. Since the fast waves are excited by two loop antennas, a large amount of the power is concentrated at $N_Z \simeq 1$ even if $\Delta\phi = 90°$. Use of four loop antennas can increase η_2 more than 90%.

4. Propagation of fast waves

The propagation of the excited fast waves measured with rf pick up loops inserted in the vacuum chamber is shown in Fig. 8. The pick up loops are located at the scrape off layer between the wall and the limiter and pick up the magnetic field of the waves. It is expected that the wave intensity measured with the loops increases when the fast waves propagate toward them. In the experimental arrangement shown in the figure, the excited waves propagate in the opposite direction when $\Delta\phi = +90°$. It is considered that the large peak near $\Delta\phi = 0°$ is related with the excitation of the coaxial mode propagating in the coaxial region between the wall and the cutoff layer of the plasma [12]. When $\Delta\phi = 0°$, 70% of the power is concentrated at $|N_Z| < 1$ as shown in Fig. 3. The sub-peak near $\Delta\phi = 225°$ ($-135°$) shows the propagation of the travelling fast waves toward the pick up loops in the plasma because the unidirectional propagation can be shown by the asymmetric wave intensity with respect to $\Delta\phi = 180°$. Penetration of the fast waves into plasma interior is not clear since the pick up loops detect the magnetic field in the scrape off layer. The probe measurement for detection of the waves in the plasma will be carried out in JFT-2M and penetration of the travelling fast waves will be clarified.

5. Conclusion

In conclusion, a high loading resistance of about 5 Ω was obtained with two loop antennas array at a frequency of 200 MHz. The coupling efficiency is as high as 80%. VSWR of the loop antenna is less than 10 and a high power of about 200 kW can be transmitted through WX-77D coaxial line. Current drive with high efficiency requires the concentration of the radiated power at the suitable N_Z spectrum region. This spectrum shaping will be done by use of four loop antennas array.

The travelling fast waves could be excited by the phase control of two loop antennas array. The waves which resemble the coaxial mode were detected when the phase difference was near $\Delta\phi = 0°$.

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References

[1] JOBES, F., STEVENS, J., BELL, R., BERNABEI, S., CAVALLO, A., et al., Phys. Rev. Lett., 52 (1984) 1005.

[2] LEUTERER, F., ECKHARTT, D., SOLDIVER, F., BECKER, G., BERNHARDI, K., et al., Phys. Rev. Lett., 55 (1985) 75.

[3] UESUGI, Y., HOSHINO, K., YAMAMOTO, T., KAWASHIMA, H., KASAI, S., et al., Nucl. Fusion, 25 (1985) 1623.

[4] MAYBERRY, M.J., PORKOLAB, M., CHEN, K.I., FISHER, A.S., GRIFFIN, D., et al., Phys. Rev. Lett., 55 (1985) 829.

[5] GOLANT, V.E., Sov. Phys. - Tech. Phys., 16 (1972) 1980.

[6] GOREE, J., ONO, M., COLESTOCK, P., HORTON, R., McNEIL, D., and PARK, H., Phys. Rev. Lett., 55 (1985) 1669.

[7] McWILLIAMS, R. and PLATT, H., Phys. Rev. Lett., 56 (1986) 835.

[8] THEILHABER, K. and BERS, A., Nucl. Fusion, 20 (1980) 547.

[9] OLSON, L., McWILLIAMS, R., GLANZ, J., AND MOTLEY, R.W., Nucl. Fusion, 24 (1984) 1085.

[10] SHOJI, T., FUNAHASHI, A., HOSHINO, K., KASAI, S., KAWAKAMI, T., et al., in Controlled Fusion and Plasma Physics (Proc. 11th Europ. Conf. Aachen, 1983), Vol.1 (1984) 55.

[11] IKEDA, Y., KIMURA, H., FUJII, T., SAIGUSA, M., IMAI, T., et al., JAERI-M Report, 84-191 (1984).

[12] WEYNANTS, R.R., in Heating in Toroidal Plasmas (Proc. 4th Int. Symp. Rome, 1984), Vol.1 (1984) 211.

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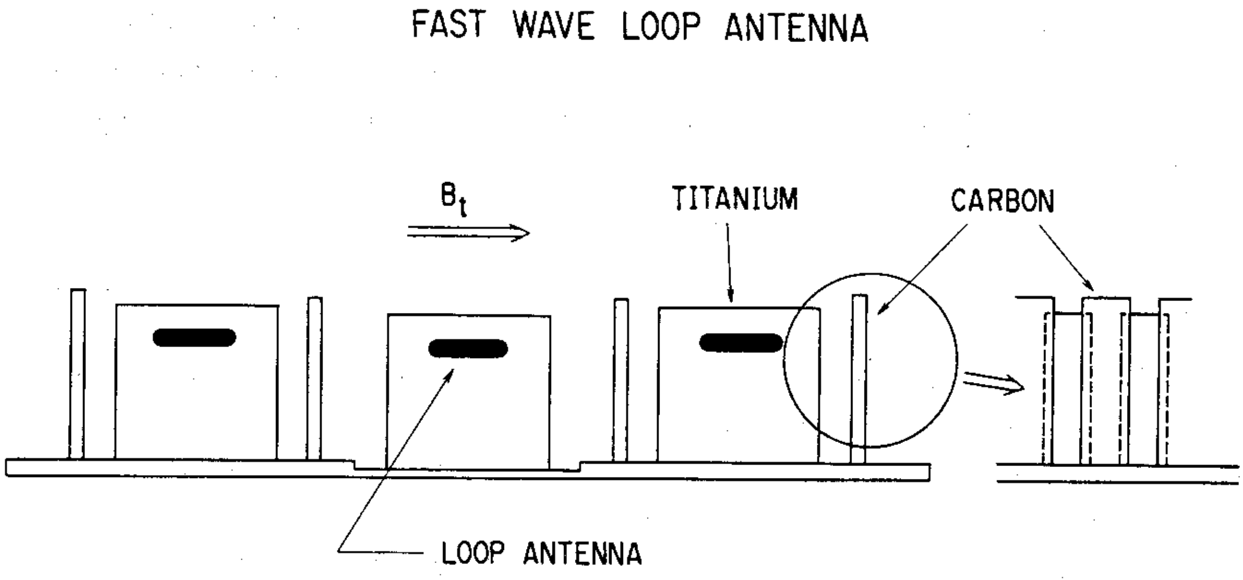

Fig. 1 Schematic view of the poloidal cross-section of three loop antennas array. Each antenna element which has a radiation length of 18 cm in the poloidal direction, is covered with single layer Faraday shields. Two loop antennas among three are used for exciting fast waves. The gap between each antenna is 10 cm.

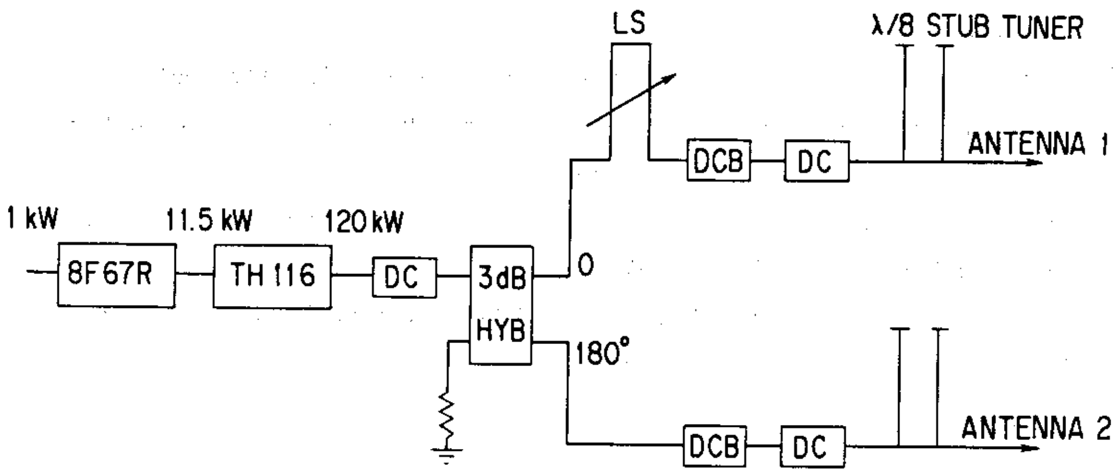

Fig. 2 Block diagram of FWCD rf system in JFT-2M. The rf power of 100 kW with a duration of 100 msec is generated at a frequency of 200 MHz.

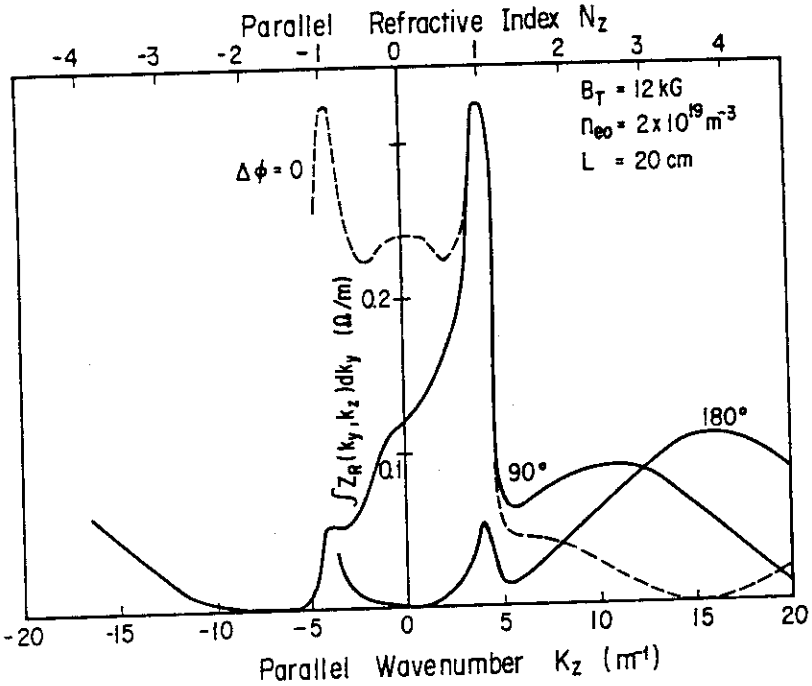

Fig. 3 K_z spectra of the loading resistance, taking the phase difference as a parameter.

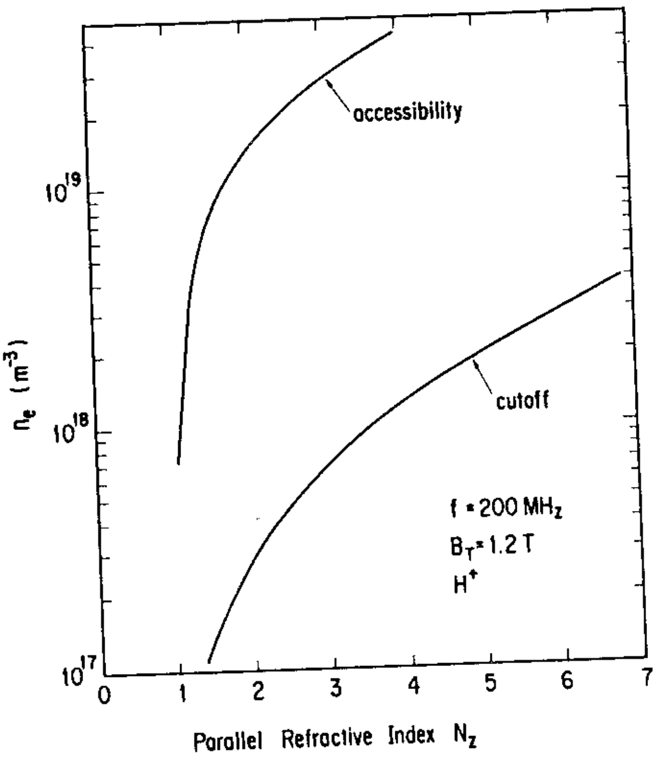

Fig. 4 Density and parallel refractive index limits for propagation of 200 MHz fast wave in JFT-2M. The fast wave can propagate in the region between two curves.

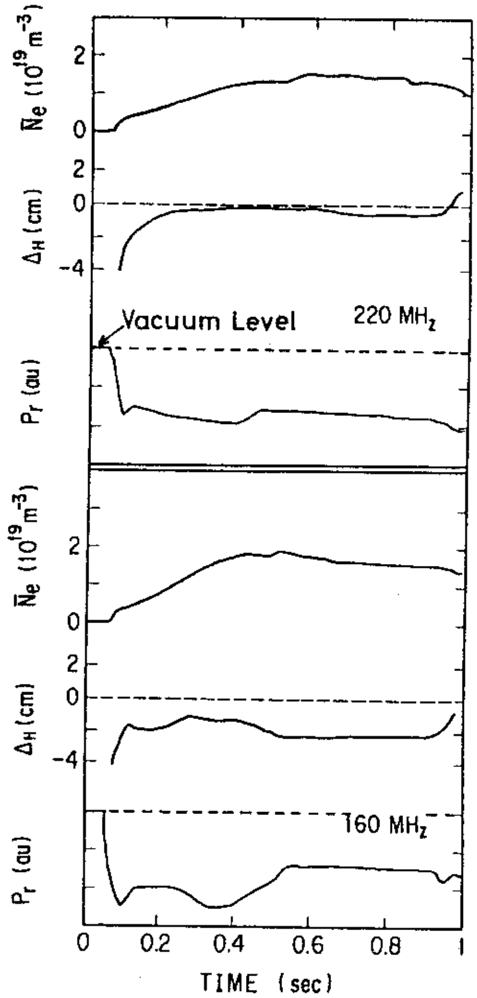

Fig. 5 Time evolution of the electron density, the horizontal displacement of the plasma column and the reflection power. The rf power of 1 kW was fed to a single antenna continuously.

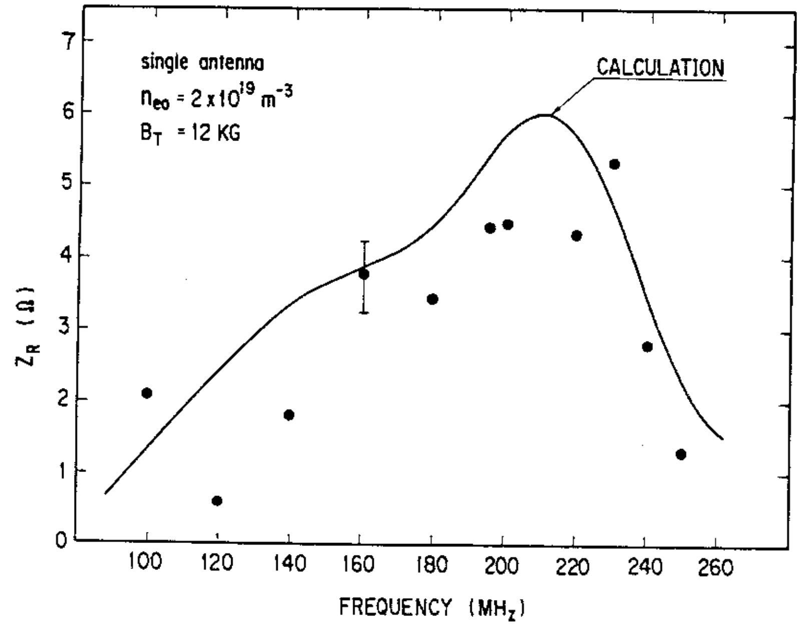

Fig. 6 Loading resistance obtained from the reflection measurements as a function of the frequency. The solid curve indicates the theoretical estimation.

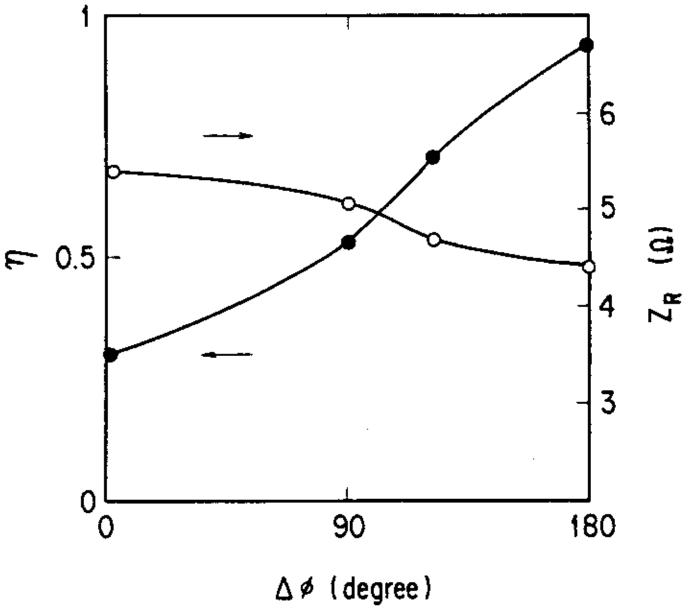

Fig. 7 Phase dependence of the loading resistance and the efficiency, η_2 when the frequency is 200 MHz and two loop antennas are employed for launching fast waves.

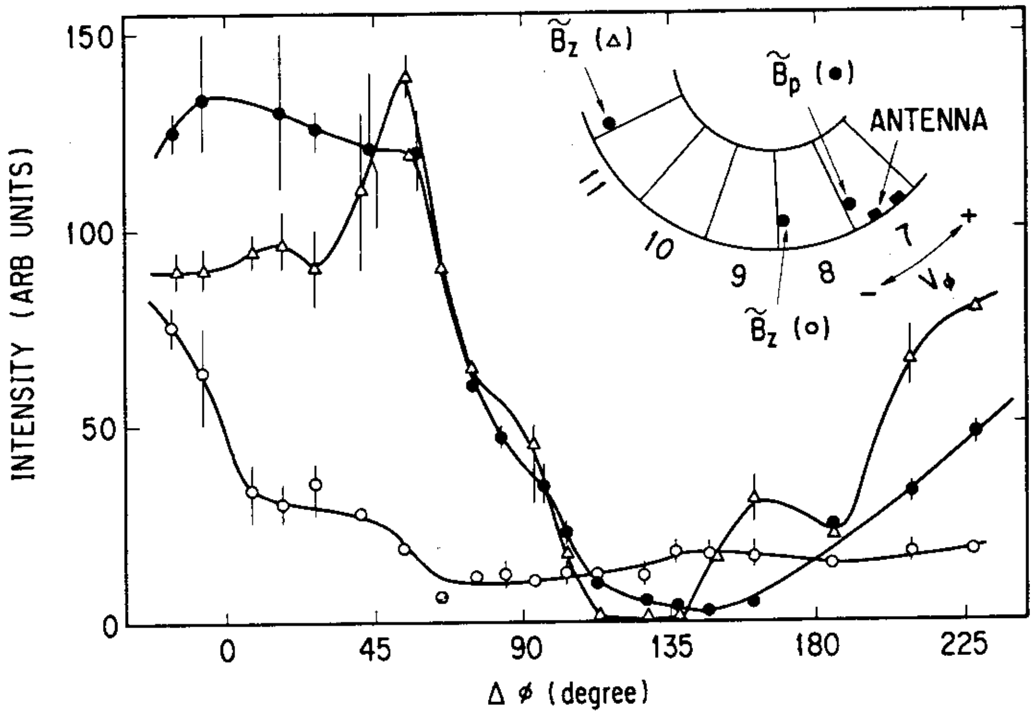

Fig. 8 Phase dependence of the intensity measured with pick up loops of $\tilde{B}$. The location of the loop antennas and pick up loops are shown in the figure. $\tilde{B}_z$ and $\tilde{B}_p$ indicate the magnetic fluctuation of toroidal and poloidal directions, respectively.