*Proceedings of the Korean Nuclear Society Spring Meeting*
*Cheju, Korea, May 1996.*

# Optimization Study of Antenna Launching Condition for Efficient FWCD in KT-2 Tokamak

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## Abstract

To derive the optimimum antenna launching condition for fast wave current drive, the propagation and absorption of the ion cyclotron range of frequencies waves are studied in a KT-2 tokamak plasma. We sove the kinetic wave equation in one dimensional slab geometry with the phase-shifted antenna array to inject the toroidal momentum to electrons. The accessibility conditions and the guidelines of the optimum antenna design for the efficient current drive are derived. The dependence of the current drive efficiency on launching conditions such as the phase and spacing is presented.

## 1. Introduction and Wave Equations

The fast wave current drive(FWCD) has been thought to be an attractive method for the seed current at magnetic axis since it can penetrate into plasma center and deposit its energy and momentum. KT-2 tokamak[1] has been conceptualized to have a large aspect ratio of 5.6 with intensive RF heating, so that it can allow advanced tokamak researches of high bootstrap current fraction and FWCD was chosen as a main drive for the seed current at center. Among a lot of issues associated with FWCD, the most important one for KT-2 is thought to be the design of antenna system for the efficient current drive, i.e. to keep the given RF energy and momentum from going to ions or other loss channels. This requires the investigation of the fast wave spectra for various wave frequencies, plasma parameters and launching conditions, such as antenna phasing, spacing and the total number of antennas. In this study, we apply the analyses of ICRF wave propagation[2,3] to obtain induced current. The kinetic treatment of dispersion relation enables the inclusion of various kinetic effects. Also, by solving the wave equation as a boundary value problem, the tunnelling effect, standing wave formation and antenna coupling can be described, which the ray tracing analysis[4] can not describe.

In a one-dimensional model of ICRF wave propagation, the magnetic field is in the z-direction and the magnitude varies in the $x$-direction as $B(x) = \frac{B_0}{1+x/R}$, simulating a toroidal system. The surfaces of plasma are at $x = \pm a$, and plasma is assumed to be homogeneous in the $y$ and $z$ direction. The plasma density and temperature profiles are assumed to be parabolic. We model the antenna is placed at $x = d$ in the low field side and carries sheet current in the $y$ direction. Then $z$ profile of the antenna current density, $J_y^A(z)$ is Fourier-decomposed as

$$J_y^A(z) = \sum_{k_z} J^A(k_z)\delta(x-d)exp(ik_z z - i\omega t) \tag{1}$$

The wave fields in the plasma are described by the Maxwell equations ;

$$\nabla \times \mathbf{E} = i\omega \mathbf{B} \tag{2}$$

and

$$\nabla \times \mathbf{B} = -i\frac{\omega}{c^2}\mathbf{E} + \mu_0(\sum_s \mathbf{J}_s + \mathbf{J}^A) \tag{3}$$

where s denotes the particle species and $\mathbf{J}_s$ is oscillating current carried by the s-th species which is calculated from the nonlocal kinetic dielectric tensor[2] ;

$$\mathbf{J}_s(r) = \int \sigma[r - r', (r + r')/2]\mathbf{E}(r')dr' \tag{4}$$

The explicit form of $\mathbf{J}_s$ was calculated with the kinetic treatment in ref. 2. For given antenna current $\mathbf{J}^A$, Eqs.(2)-(3) are solved to obtain the wave field, which is connected to the vacuum field. In the vacuum region, the solution is determined by the boundary conditions at $x = \pm b$ (on the wall) and $x = d$ (on the antenna). Across the current sheet,

$$\frac{dE_y}{dx}\Big|_{d-0}^{d+0} = -i\omega\mu_0 J_y^A \tag{5}$$

has to be satisfied due to the jumping of $\frac{dE_y}{dx}$, and at walls, we use boundary condition as

$$\frac{1}{E_y}\frac{dE_y}{dx}\Bigg|_{\pm b} = \mp\sqrt{\{k_z^2 - (1 + \frac{i\sigma_W}{\omega\epsilon_0})\frac{\omega^2}{c^2}\}}. \tag{6}$$

In Eq.(6), $\sigma_W$ denotes the conductivity of the wall and RF energy is dissipated on the wall due to the finite resistivity. At the plasma-vacuum interface, we employ the boundary condition of perfect reflection of the ion Berstein wave.

## 2. Optimum Antenna design

For the typical parameters of the KT-2 tokamak, we first investigate the accessibility of the fast wave for the wave frequency; 30 $MHz$ and 225 $MHz$. Fast wave can be absorbed by electrons depending on the parallel wave number $k_z$. To find out the accessible region of $k_z$, we investigate the spectra of power absorptions as a function of the parallel wave number $k_z$. Fig. 1 shows the power absorptions and the current drive efficiency defined as the ratio of the total induced current to the total emitted power from the antenna for $n_0 = 1 \times 10^{20}\, m^{-3}$, $T_0 = 5\ keV$ and $\omega = 30\ MHz$, and the antenna current density of $J(k_z) = 1\ A/m$. The current drive efficiency becomes a maximum at $k_z = 3\ m^{-1}$ and decreases as $k_z$ increases. Power absorption spectra show several sharp peaks due to cavity resonance effect[5]. Power absorption by the ion is negligible in this case. Upper limit of accessible region is found to be 12 $m^{-1}$. $T_0 = 5\ keV$ and $\omega = 225\ MHz$. The lower and upper limit of accessible region increase and found to be $k_{z,min} = 12\, m^{-1}$ and $k_{z,max} = 90\ m^{-1}$. The current drive efficiency becomes a maximum around $k_z = 18\, m^{-1}$ and is bigger than low frequency case(Fig. 1). In this case power absorption by ion is not negligible up to $k_z = 20\ m^{-1}$ region.

We consider multiple antenna at location $z_j = (j-1)\Delta z$ with phase $\phi_j = (j-1)\Delta\phi$ ($j$ runs from 1 to $N$, where $N$ is the total number of antennas). For constant antenna current densities, i.e. $J_j^A(z) = J_0$, the spectrum of the antenna current is given by

$$|J(k_z)| = 2J_0 \left|\frac{sin(k_z \Delta W/2)}{k_z}\right| \left|\frac{1 - cos N(\Delta\phi - k_z\Delta z)}{1 - cos(\Delta\phi - k_z \Delta z)}\right| \tag{7}$$

Here, $\Delta W$ represents the width of the antenna. The dominant spectrum peak and its width are calculated as

$$k_{z,m} = \frac{\Delta\phi - 2\pi m}{\Delta z} \quad \text{for m=0, } \pm 1, \pm 2, \cdots \tag{8}$$

$$\Delta k_z = \frac{4\pi}{N\Delta z}. \tag{9}$$

Eq.(9) shows that as total number of antennas increase, $\Delta k_z$ decrease. For the efficient current drive, the antenna parameters can be optimized by requiring that the current is driven mainly by the $m = 0$ spectrum peak corresponding to the optimum wave number found in Figs. 1 - 2 and the $m = 1$ spectrum peak is removed from the accessibility since it induces the counter current and reduces the current drive efficiency.

### 3. Dependence on Launching Conditions

Fig. 3 shows the phase dependence of the power absorption, the induced current and the average resistance($\bar{R} = \sum_{j=1}^{N} Re(Z_j)/N$) and reactance ($\bar{X} = \sum_{j=1}^{N} Im(Z_j)/N$) per an antenna for the case of N=8 and $\Delta z = 12.2\,cm$, where $Z_j$ is the loading impedance of $j$-th antenna defined by

$$Z_j = \frac{\int dz E_y(z) J_j^A(z) exp(i\phi_j)}{\int dz J_j^A(z)^2}. \tag{10}$$

The power absorption by electron is almost constant as shown in Fig. 3(a). The loading resistance increases as $\Delta\phi$ and becomes a maximum around $\Delta\phi = 70°$, while the loading reactance is almost constant(Fig. 3(b)). Fig. 3(c) shows that the current drive efficiency increases as $\Delta\phi$ and becomes a maximum at $\Delta\phi = 70°$. Fig. 4 shows spatial structure of energy flux and electron power absorption(a), induced current(b) and the electric fields($E_y$(c), $E_z$(d)) for the case of $\Delta\phi = 70°$ and N=8. The decrease of energy flux shows the spatial damping of the incident fast wave and the induced current profile follows the electron absorption profile. Electron power is absorbed in the central region and results in peaking of the induced current in the central region.

When we increase the antenna spacing, $\Delta z = 24.4\,cm$, as in the $\Delta z = 12.2\,cm$ case, the power absorption by electron is almost constant. The loading resistance is a maximum at $\Delta\phi = 130°$, while the loading reactance is almost constant. The current drive efficiency shows several peaks since different $k_z$ values can be selectly excited due to smaller $\Delta k_z$. Maximum efficiency can be obtained by selectably exciting $k_z = 9\,m^{-1}(\Delta\phi = 130°)$.

For the case of high frequency excitation; $\omega = 225\,MHz$, the exclusion of m=1 peak of the antenna current spectrum from the accessibility region is hard to be satisfied with realizable antenna spacing. We investigate the characteristics of high frequency excitation with the antenna spacing $\Delta z = 12.2\,cm$. Fig. 5(a) shows the phase dependence of power absorptions when the total number of antenna, $N = 8$. Power absorption by ions is not negligible and bigger than absorption by the electrons for $20° < \Delta\phi < 120°$. Both the loading resistance and reactance show a maximum around $\Delta\phi = 90°$(Fig. 5(b)) and the maximum curren drive efficiency is found to be 0.02 $A/W$(Fig. 5(c)) which is much smaller than the low frequency excitation case since $m = \pm 1$ peak are accessible and they reduce the current drive efficiency. The the energy flux, absorptions and induced current profiles are shown in Fig. 6(a) and (b) for $\Delta\phi = 90°$ at $z = 0$ plane. As incident fast wave propagates in the central region, the power absorption by ion occurs around $x = 0$ and the electron absorption occurs for the region, $-0.1\,m < x < 0.1\,m$(Fig. 6(a)). As shown in Fig. 6(b) the induced current profile follows the electron absorption profile. Corrugation in the power absorption and current profile is due to the formation of the standing wave. Due to the high phase velocity of the wave, the coupling between the wave and the electrons is weak and the incident wave is not completely absorbed in a single pass and reflected at the high field side wall. The electrons absorb the power in a multi pass process.

## 4. Summary

We have studied the characteristics of the fast wave current drive in KT-2 tokamak plasma by solving the kinetic equation of the ICRF wave in one dimensional slab model. To find out the design guidelines for the optimum current drive, we investigated the accessibility of the fast wave for low($\omega = 30\ MHz$) and high($\omega = 225\ MHz$) frequency cases. From the accessibility conditions, we obtained the optimum launching condition such as the antenna spacing, phase and total antenna number. For low wave frequency, the accessible $k_z$ region is small and the optimum parallel wave number is found to be $3\,m^{-1}$. For high wave frequency, both $k_{z,min}$ and $k_{z,max}$ increase and the optimum parallel wave number is found to be $18\,m^{-1}$. The wave propagations are dominated by the cavity resonance due to the formation of standing wave for both cases. For the cases considered in this study, the maximum current drive efficiency is estimated as $0.05\,A/W$ for low frequency excitation with the antenna phase, $\Delta\phi = 70°$ and total antenna number, $N = 8$.

## References

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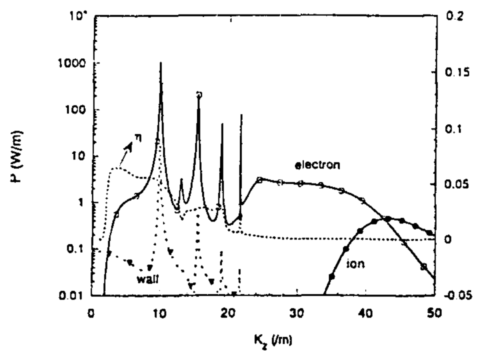


Fig.1 Absorption power spectrum vs. $k_z$

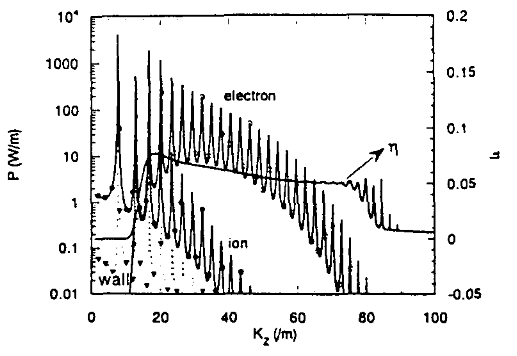


Fig.2 Absorption power spectrum vs. $k_z$

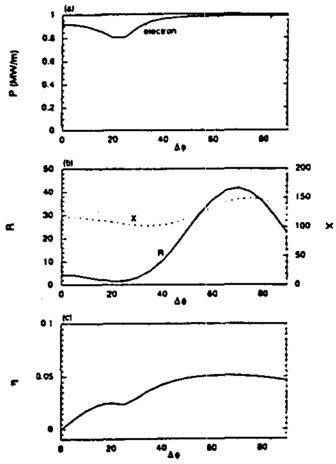

Fig. 3 Phase dependence of (a) electron power absorption (b) loading resistance, R(Ω/m) and reactance, X((Ω/m) and (c) current drive efficience.

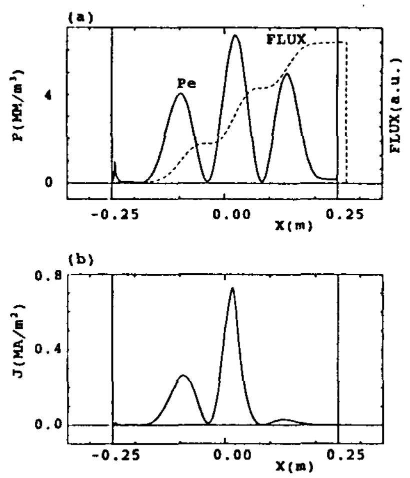


Fig. 4 Spatial structure of (a) energy flux and electron power absorption, and (b) induced current.

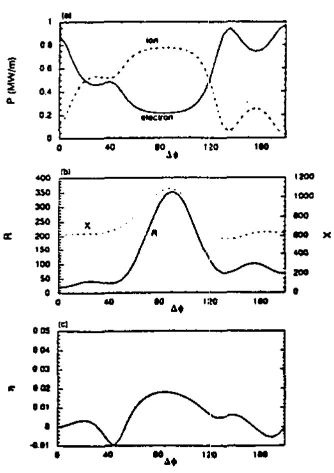

Fig. 5 Phase dependence of (a) electron power absorption (b) loading resistance, R(Ω/m) and reactance, X((Ω/m) and (c) current drive efficience.

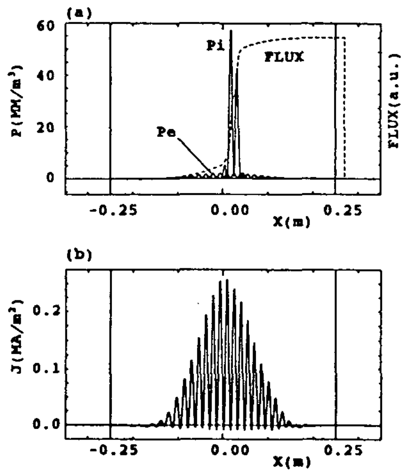


Fig. 6 Spatial structure of (a) energy flux and electron power absorption, and (b) induced current.