Results of Lower Hybrid Wave Experiments Using a Dielectric Loaded Waveguide Array Antenna on TST-2

T. Wakatsuki[a], A. Ejiri[a], T. Shinya[a], Y. Takase[a], H. Furui[a], J. Hiratsuka[a], K. Imamura[a], T. Inada[a], H. Kakuda[a], H. Kasahara[b], Y. Nagashima[c], K. Nakamura[a], A. Nakanishi[a], T. Oosako[a], K. Saito[b], T. Seki[b], F. Shimpo[b], M. Sonehara[a], H. Togashi[a], S. Tsuda[a], N. Tsujii[a], T. Yamaguchi[a]

[a]The University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa city, Chiba, Japan, 277-8561
[b]National Institute for Fusion Science, 322-6, Shimoishi, Toki city, Gifu, Japan, 509-5292
[c]Kyushu University, 6-1, Kasuga-koen, Kasuga city, Fukuoka, Japan, 816-8580

Abstract. Lower hybrid current drive experiments were performed on the TST-2 spherical tokamak (R = 0.38 m, a = 0.25 m, B_t = 0.3 T, I_p = 0.1 MA). A waveguide array antenna consisting of four dielectric (alumina, ε_r = 10.0) loaded waveguides was used. The coupling characteristics were investigated over a wide range of input power (0.1 W – 40 kW). The reflection coefficient of this antenna increased when the input power exceeded approximately 1 kW. This result was compared with a numerical simulation based on the finite element method (FEM). The ponderomotive effect was calculated for the wave field calculated by COMSOL [1]. This calculation also showed variation of the reflection coefficient with the input power. Non-inductive plasma current start-up to 10 kA was demonstrated using 40 kW of lower hybrid wave (LHW) power. The current drive figure of merit ($\eta_{CD} = I_p\, n_e\, R\ /\ P_{RF}$) of this antenna was higher than that obtained using the combline antenna, which is designed to excite a travelling fast wave. The best current drive efficiency was obtained in the case in which the $n_{\|}$ (= $ck_{\|}/\omega$) spectrum of the excited LHW was peaked around 9 and the toroidal field was higher than in previous experiments

Keywords: Lower Hybrid Wave, Spherical Tokamak, Plasma Current Start-up, TST-2
PACS: 52.35.Hr, 52.55.Fa, 52.55Wq, 52.50Sw

INTRODUCTION

Plasma current start-up experiments using waves in the lower hybrid frequency range has been performed on the TST-2 spherical tokamak. It is well known that accessibility of the lower hybrid wave (LHW) to the plasma core is severely limited in ST plasmas. However, LHW can be used for the plasma start-up phase if the plasma density is kept sufficiently low. At present, plasma current ramp-up to 10 kA has been achieved using a dielectric (alumina) loaded waveguide array (or "grill") antenna. As the frequency of LHW on TST-2 was 200 MHz, we have to use a dielectric to make the size of the waveguide smaller than the largest port on TST-2. The input power to each waveguide element was limited to 25 kW to avoid breakdown at the coax-waveguide transition. This limit kept the electric field inside the alumina to less than 10 kV/mm, which is a typical DC breakdown electric field. In spite of this limitation, the advantage of this type of antenna is the capability of exciting LHW with different $n_{\|}$, unlike in the previously used travelling fast wave antenna (the combline antenna [2]). In this paper, the coupling characteristics of this antenna is discussed, including the effect of ponderomotive force. The dependence of the current drive efficiency on $n_{\|}$ and comparison with that obtained using the combline antenna are also discussed.

COUPLING CHARACTERISTICS

The coupling characteristics of this antenna were investigated over a wide range of input power (fig.1(a)). The LHW was launched into inductively sustained plasmas. When the movable private limiter surrounding the grill antenna was placed 10 mm inward (towards the plasma) from the surface of the antenna, the reflection coefficient was over 50 % at high power, but decreased to 30 % at low power (less than 100 W). On the other hand, when the private limiter was placed behind the antenna surface, this power dependence was not observed.

Radiofrequency Power in Plasmas
AIP Conf. Proc. 1580, 422-425 (2014); doi: 10.1063/1.4864578

This non-linear behavior could be explained by the ponderomotive effect, which reduces the plasma density in front of the antenna. The antenna-plasma coupling could deteriorate if the plasma density becomes lower than the cutoff density for the excited lower hybrid wave. The ponderomotive effect is counteracted by the rapid plasma transport along the magnetic field when the private limiter does not intersect magnetic field lines in front of the antenna. Therefore, the deterioration of coupling should be observed only when the private limiter intersects magnetic field lines in front of the antenna. This conjecture is partly confirmed by the small Langmuir probe tip installed at the bottom of the antenna. The floating potential measured by this probe dropped as the input power exceeded 100 W (fig. 1(b)). Although the floating potential is not directly related to the plasma density, it is clear that the plasma condition changed with the RF power.

This result was compared with the results of numerical simulation based on the finite element method (FEM). This simulation is similar to that performed using the POND code [3]. The ponderomotive potential was calculated for the wave field calculated by COMSOL using the formula [4],

$$\Phi_{\mathrm{p}} = \frac{e}{m}\left[\frac{|E_z|^2}{\omega^2} + \frac{|E_x|^2 + |E_y|^2}{\omega^2 - \Omega_c} + \mathrm{Im}\left\{\frac{\Omega_c\left({}^{*}E_x E_y - E_x {}^{*}E_y\right)}{\omega\left(\omega^2 - \Omega_c{}^2\right)}\right\}\right] \quad (1),$$

where Φ_{p} and Ω_c denote the ponderomotive potential and the cyclotron frequency, respectively. The change of the density was calculated using this potential. This simulation showed variation of the reflection coefficient with the input power (fig. 1(c)), assuming that the private limiter was placed 10 mm away from the antenna surface (the same condition as for the black trace in fig. 1(a)), and the plasma density at the edge was 1 x 10^{18} m^{-3}. The density inside the private limiter was initially assumed to decrease linearly. A Langmuir probe placed on the mid-plane and 120 degrees away from the antenna toroidally showed that the electron density was 1 x 10^{18} m^{-3} and the electron temperature was 1 - 10 eV at the plasma edge. The inflection points of the simulated reflection coefficient plotted versus input power shifted towards higher power as the prescribed plasma temperature increased because the change in density was determined from the equilibrium relationship between the plasma pressure and the ponderomotive force. The inflection point of the experimentally measured reflection coefficient was between 100 W and 1 kW. The corresponding temperature in the simulation was 5 - 10 eV. This result falls inside the approximate range of the electron temperature measured by the mid-plane Langmuir probe.

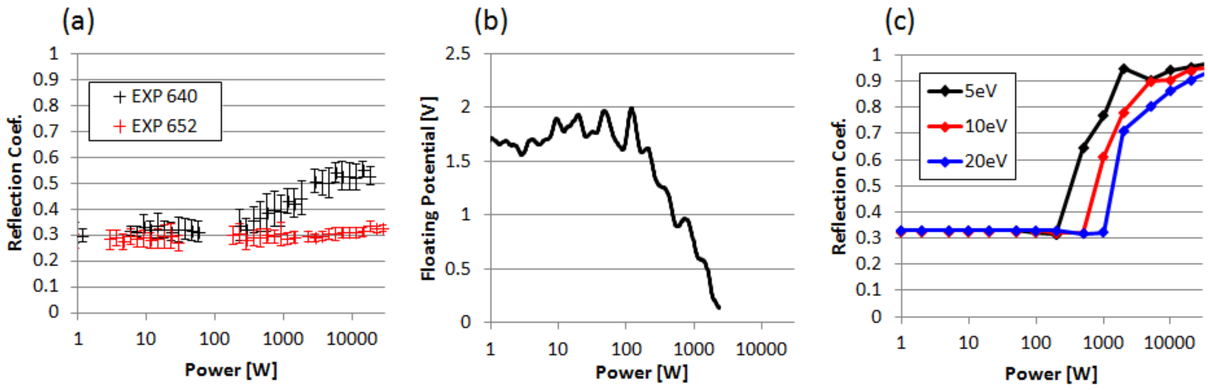

FIGURE 1. Experimentally obtained power dependences of the reflection coefficient (a) and the floating potential (b), and the reflection coefficient obtained in simulation (c). The black and red symbols in (a) denote the reflection coefficients when the private limiter was placed at *R* = 0.640 m and 0.652 m, respectively (the surface of the antenna was located at *R* = 0.65 m). Three traces in (c) denote different temperature cases: 5 eV (black), 10 eV (red) and 20 eV (blue).

CURRENT DRIVE EFFICIENCY

The dependences of the current drive efficiency on the toroidal field, vertical field, input power and excited $n_{||}$ were studied. Non-inductive plasma start-up experiments using this antenna were performed at relatively low plasma current (4kA). This result is summarized in fig. 2. The highest plasma current was achieved when the phase difference between adjacent waveguides was 90 degrees ($n_{||}$ = 8.9). The brightness of X-ray emission also changed with the phase difference. The bulk electron temperature of this plasma is assumed to be very low so that the absorption of LHW is not strong unless $n_{||}$ is sufficiently high. However, the directivity of the excited wave spectrum deteriorates as the phasing increases beyond 90 degrees. In addition, waves with higher $n_{||}$ couple to lower energy electrons with high collisionallity, so deterioration of the current drive efficiency at high $n_{||}$ is expected. The plasma current must be high enough to confine the high energy electrons produced by LHW. Consequently, the X-ray brightness should have a double peaked structure. Another experiment aimed at achieving higher plasma currents (up to 7 kA) also showed that the highest plasma current was achieved with a 90 degree phasing. The maximum plasma current achieved so far using this antenna is 10 kA with this phasing. The discharge waveform of this operation is shown in fig. 3.

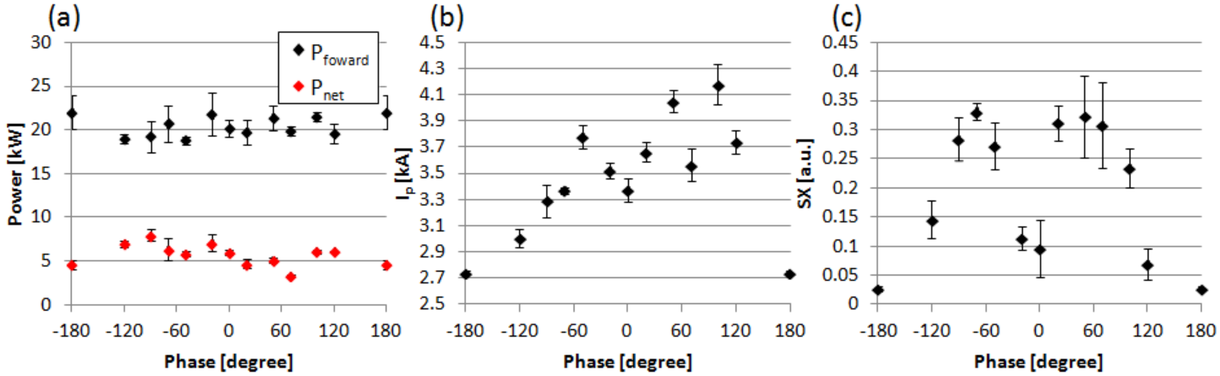

FIGURE 2. Dependences of (a) forward RF power and net RF power, (b) driven plasma current, and (c) soft X-ray emission in the energy range 1-10 keV on the phase difference between adjacent waveguides obtained in non-inductive plasma start-up experiments..

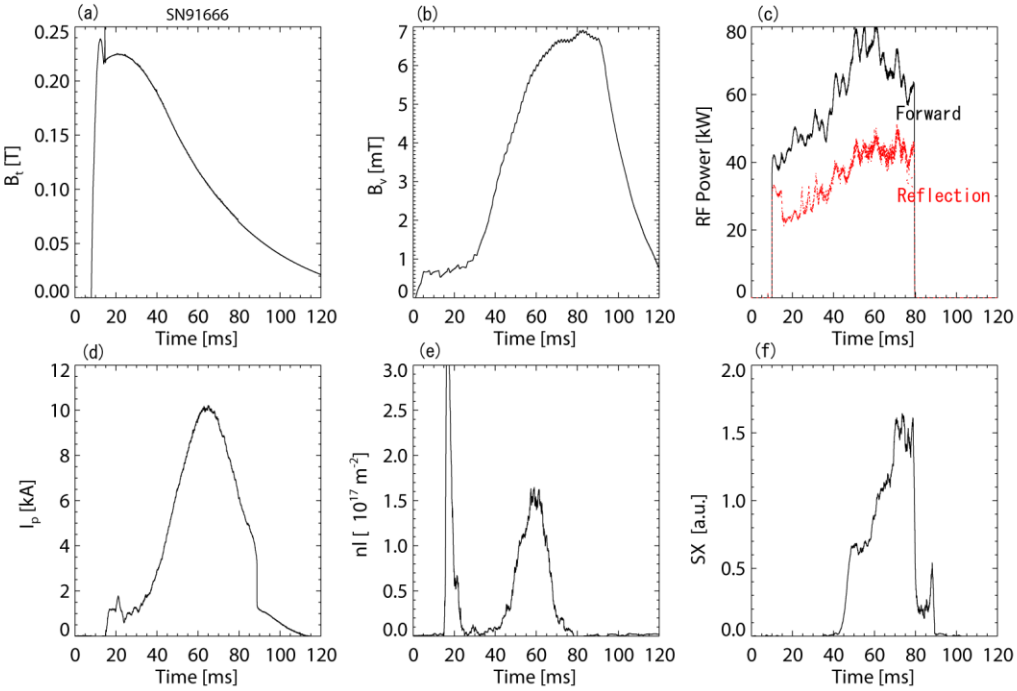

FIGURE 3. The waveforms of a discharge with 10 kA plasma current. (a) The toroidal field, (b) the vertical field, (c) forward (black) and reflected (red) RF powers, (d) the plasma current, (e) the line integrated density through the vertical chord at $R = 0.39$ m and (f) soft X-ray emission in the energy range 1-10 keV are shown.

The current drive figure of merit ($\eta_{CD} = I_p n_e R / P_{RF}$) was calculated for discharges with different plasma currents, input powers and toroidal fields, and compared with those obtained in the experiments using the combline antenna (fig. 4). The highest η_{CD} on TST-2 was achieved using the grill antenna. This result was due to the lower RF power needed in the experiments using the grill antenna. The combline antenna was designed to excite the fast wave. Therefore, direct excitation of LHW, which is the slow wave, is possible only when the fast wave is evanescent at low density. But the efficiency of LHW excitation is not as efficient as the grill antenna. As is clearly shown in fig. 4 (b), another reason for higher η_{CD} is the higher toroidal field (0.2 T) that was available for the experiment with the grill antenna. The higher magnetic field operation became possible because the 8.2 GHz EC wave system was installed on TST-2 for pre-ionization. The accessibility condition for the LHW is satisfied at higher plasma density with higher toroidal field. A simulation using the TORLH full-wave code has shown that higher magnetic fields (0.3 T) would be needed for LHW to access the plasma core when the central electron density is 1 x 10^{18} m^{-3} [5].

The new traveling wave antenna which can excite LHW directly was installed on TST-2 in the spring of 2013 [6]. This antenna can couple more than 90 % of input power to the plasma and transmit more than 100 kW. The excited $n_{||}$ will have a peak at 5.2 which is near to the optimum value obtained in the experiment. We will compare η_{CD} of this antenna to those presented in this paper. The effectiveness of this antenna will be assessed using wave measurement data and X-ray emission data.

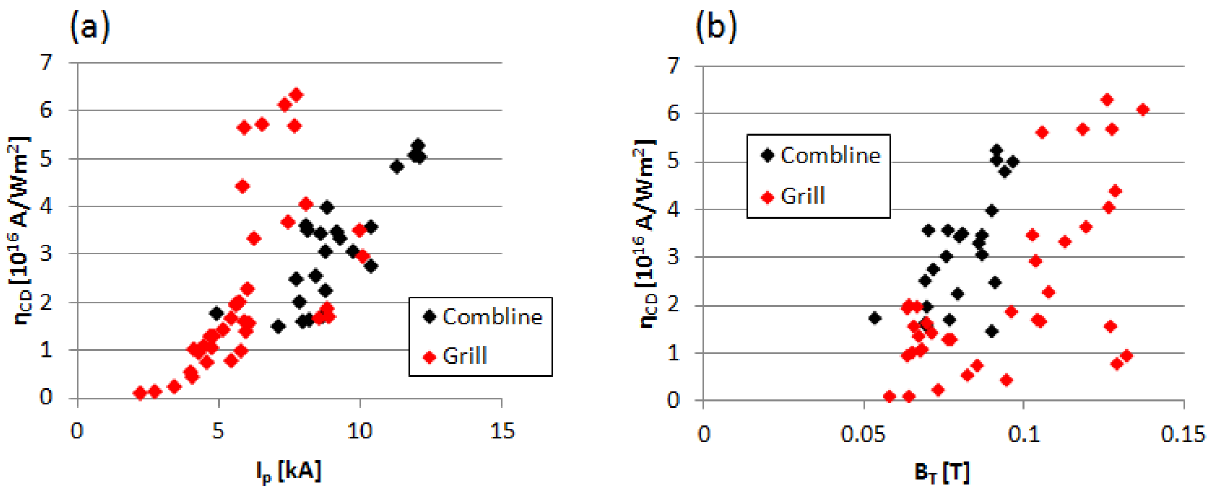

FIGURE 4. η_{CD} obtained in experiments using the combline antenna (black symbols) and the grill antenna (red symbols) are plotted against the plasma current (a) and the toroidal field (b).

ACKNOWLEDGMENTS

This work is supported by JSPS Grant-in-Aid for Scientific Research (S) 21226021, Grant-in-Aid for JSPF fellows, and NIFS Collaboration Research program NIFS12KNWR001

REFERENCES

1. COMSOL Multiphysics, http://www.comsol.com
2. T. Wakatsuki, et al., *IEEJ transactions on Fundamentals and Materials*, IEEJ, 132, 7 (2012)
3. O. Meneghini, et al., "Full-wave modeling of lower hybrid waves on Alcator C-Mod", Ph.D. thesis, Department of Nuclear Science and Engineering, MIT (2012).
4. J. R. Cary and A. N. Kaufman, *Physical Review Letters*, APS, 402, 39 (1977)
5. T. Wakatsuki, et al., *AIP Conference Proceedings*, AIP, 1406, 431 (2011)
6. Y. Takase, et al., "Characteristics of A Novel Lower Hybrid Wave Antenna for The TST-2 Spherical Tokamak", these proceedings (2013)