Experimental Study of a Lower Hybrid Wave Multi-junction Coupler in the HT-7 Tokamak

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Abstract. A phase-controlled lower hybrid wave (LHW) multi-junction (MJ) coupler has been developed in the HT-7 tokamak. Simulations show that it is more effective to drive plasma current than a traditional coupler. Studies of the plasma and wave coupling experiment show that good coupling efficiencies with low reflection coefficients (RC) below 10% are obtained, suggesting that the plasma density at the grill mouth satisfies the coupling condition. The plasma displacement in one discharge has little effect on the wave-plasma coupling, as is mainly ascribed to the non-shifted last closed magnetic flux surface (LCFS) determined by the fixed poloidal limiter in our experiments. Investigations of the capability of current drive of the MJ antenna show that there is an optimized density region where good drive efficiency is obtained. The efficiency is strongly dependent on power spectrum. The experimental drive efficiency of the MJ antenna is higher than that of the traditional one. Studies indicate that the discrepancies of impurity concentration, plasma temperature and counter-direction driven current fraction contributed from the negative spectrum could be responsible for the higher drive efficiency of the MJ coupler.

1. Introduction

Lower hybrid current drive (LHCD) is an effective way to drive plasma current, modify plasma current profile, thereby improving plasma confinement in a tokamak. A 1.2 MW (12x100kW) LHCD system [1] with 12 klystron amplifiers operating at a frequency f=2.45GHz has been installed in the HT-7 tokamak [2] to drive plasma current. LHW is fed into a tokamak plasma by an antenna, which is one of key factors determining the launched spectrum. It is very necessary to study the LHW antenna and its experimental characteristics.

To realize a high performance plasma, a phase-controlled LHW MJ coupler (3(row) × 4(column) × 4(subwaveguide)) has been developed [3] in the HT-7 tokamak since 2001 campaign. With the newly developed MJ coupler, an improved plasma [4] with an internal transport barrier (ITB) formation characterized by an ion and an electron temperature profile has been reported in the last IAEA meeting, demonstrating its capability of modifying plasma current and improving plasma confinement. Also, the edge plasma fluctuation suppressed by LHCD with the MJ coupler has been analyzed [5,6]. Here, we would like to investigate the characteristics of the MJ grill, study the wave-coupling characteristics, and analyze the current drive efficiency. In all of the experiments, deuterium is selected as the working gas.

The manuscript is set as follows: the characteristics of the MJ grill, as well as its comparison with the traditional one, are described in section 2, followed by the analysis of wave-plasma coupling experiments. The current efficiencies of the two antennae are compared and investigated in section 4. At last, a brief conclusion is given in section 5.

2. Characteristics of Multijunction Grill

HT-7 tokamak is a middle-size (major radius 1.22m, minor radius 0.28m) and a limiter configuration device with a circular geometry. The MJ grill mouth structure is designed to match the plasma shape so that the effect of this mismatch on the wave-plasma coupling is very small. As shown in Fig.1, compared to the traditional coupler, utilized before 2001 campaign, that only consists of 12 waveguides in one row, one of the most prominent improvements is that the 12 waveguides are arranged with an array of 3 row and 4 column, and that each main waveguide is divided into 4 subwaveguides with a fixed phase difference ($\sim 90^0$) resulting from a built-in phase shifter between them. According to M. Brambilla theory [7], the power spectra launched by the MJ and the traditional coupler are shown in Fig. 2, in which magnifications of the main lobe for the two couplers are also superimposed, where $N_{//}^{peak}$ is the peak value of the parallel refractive index of main lobe. It is seen that, compared to the spectrum with a half width $\Delta_{HFWD}\sim 0.62$ of the traditional coupler, a more asymmetric one with a narrower half width ($\Delta_{HFWD}\sim 0.53$) is obtained for the MJ grill, which is beneficial for current drive and controlling current profile at partly costing its capacity of heating electron. In order to demonstrate the more efficient drive current power of the MJ antenna, a ray tracing code [8] is utilized to calculate wave power deposition for the two types of grill, from which a non-inductive current can be estimated further with a Fokker-Planck equation [8]. In the code, the positive and the negative components of the spectrum are both considered. For the sake of simplicity, it is assumed that the mechanism of interaction of plasma and wave with positive and negative parallel refractive index is same, but the driven currents are in opposite direction. With identical plasma parameters and the spectrum shown in Fig.2, simulated power deposition profiles in Fig. 3 show that there exists little difference between the depositions contributed from the positive spectrum component for the MJ coupler and the traditional one, whereas an obvious difference occurs between the contributions from the negative spectrum component for the two antennae. Since the power depositions from the positive spectrum are almost the same and the fractions of the driven current calculated using

Fig. 1 Structure of grill mouth (left: MJ, right: traditional)

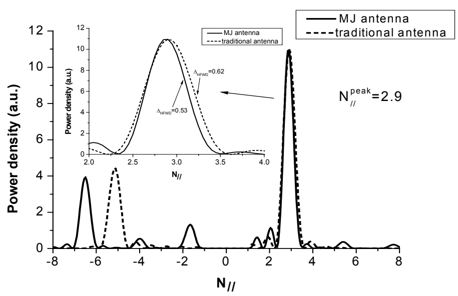

Fig. 2 Launched spectrum by MJ and traditional antenna

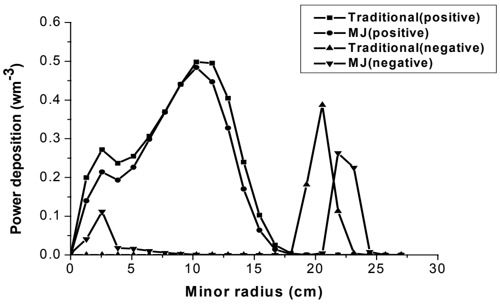

Fig. 3 Simulated power deposition for the positive/negative spectra (shown in Fig.2) launched by MJ and traditional antenna

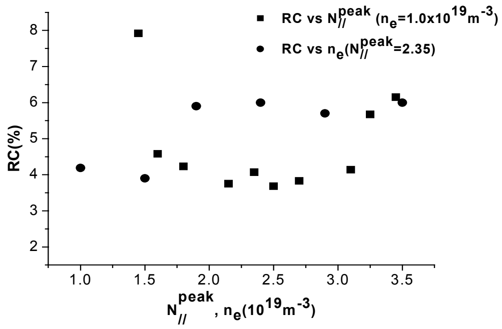

Fig. 4 Dependence of reflection coefficients on spectrum and density

a two-dimensional Fokker-Planck equation are almost equal, the positive components will not lead to a large discrepancy of the drive efficiency. It should be pointed that, in LHCD experiments, the driven current is determined by the wave propagating in both co- and counter-direction. Though the driven current by the positive spectrum is almost same for these two antennae, further calculations show that, for the traditional antenna, the current driven by the negative/counter-direction component accounts for ~20% of that driven by the positive spectrum, obviously lager than the value (<5.0%) of MJ coupler. Such larger component in the opposite direction results in a reduction of the total driven current. These results suggest that, mainly because of the more asymmetric characteristic, the drive efficiency of the MJ grill is larger than that of the traditional one.

3. Investigation of Wave-plasma Coupling Experiments

Using the MJ coupler, plasma and wave coupling experiment with a plasma current Ip~120kA, performed by scanning plasma density with $N_{//}^{peak}$~2.35 and $\Delta\Phi$ from -150^0 to 180^0 with a central averaged line density (n_e) of $1.0\times10^{19}m^{-3}$, correspondingly, $N_{//}^{peak}$ varies from 1.45 to 3.45, was studied by analyzing the reflection coefficient determined by a bi-directional coupler. The reflection coefficient, which is a main indicative of wave-plasma coupling, was roughly estimated by the ratio of reflected and incident power. Results displayed in Fig. 4 show that good coupling efficiencies with low reflection coefficients (RC) below 10% are obtained for the both scanning cases. Especially, lower reflections are observed in the range of $1.5\leq N_{//}^{peak}\leq3.0$, beyond which the reflection increases, suggesting that an optimized spectrum is required for a better coupling.

The grill-mouth density, $n_{e,grill} = n_{e,LCFS}\cdot\exp(-\frac{d}{\lambda_{SOL}})$, dominated by the distance d between the LCFS and the grill mouth, plays a dominant role in determining the wave-plasma coupling, where $n_{e,LCFS}$ and λ_{SOL} is the density at the LCFS, the decay length in the scrape of layer, respectively, which are measured by Langmuir probes. Coupling of wave-plasma requires the plasma density at the grill mouth to be above a cut-off density defined as $n_{e,co} = (\omega^2 m_e)/(4\pi e^2)$, where ω is the wave frequency, m_e the electron mass and e the electronic charge. Otherwise, the coupling will deteriorate and the reflection will increase, hence giving rise to an arc in the waveguides. More precisely, for good coupling an optimal density required at the antenna aperture is given by [9] $n_{e,grill}^{opt} \geq N_{//}^2 n_{e,co}$, where $N_{//}$ is the component of the refractive index of the wave parallel to the magnetic field. For the HT-7 tokamak, the cut-off density at the frequency of 2.45GHz is about $7.4\text{x}10^{16}\text{m}^{-3}$, and the plasma density at the grill mouth is about $1.5\text{x}10^{18}$.exp (-1.5/1.0)~$3.23\text{x}10^{17}\text{m}^{-3}$. The low reflections in the density and the spectrum scan suggest that the plasma density in front of the grill mouth satisfies the coupling condition, which is demonstrated by the above estimation. This is mainly because the grill is very close (d~1.5cm) to the LCFS plasma and the decay length (λ_{SOL} ~ 1.0cm) is not too small, so that the ratio of d/λ_{SOL} is not large enough to reduce the mouth density to the cut-off value. The effect of spectrum on reflection is due to the interaction of wave between waveguides because their propagations are different at different phase difference, which is in agreement with experimental and theory results reported in Tore-supra [10]. With the increase of $N_{//}$, the optimal coupling condition is not satisfied very well. This is another reason for the deterioration of the coupling when $N_{//}^{peak}$ >3.0.

With the density variation, the change of reflection is not as obvious as that of the spectrum case. This indicates that once the coupling condition is satisfied, the dependence of coupling on density is weak. It is still not understood why the little increase of reflection at the density of $1.9\times10^{19}\text{m}^{-3}$ is observed, for according to M. Brambilla theory, on condition that the edge density is not excessive enough to lead to high heat flux, the increasing density would be beneficial to the wave-plasma coupling. Whether this is caused by the measurement error or it is due to the change of density gradient in front of the antenna is not known yet.

The coupling experiments were also investigated with $N_{//}^{peak}$ =2.35 by moving the plasma horizontal displacement from inside (-4.0cm) to outside (2.5cm), and then to inside (-1.5cm) again in one discharge (#48003) (see Fig.5) with a plasma current Ip~110kA, ne~$1.3\text{x}10^{19}\text{m}^{-3}$, a toroidal magnetic field B_T~1.9Tesla, and an LHW power P_{LHW}~175kW. In the experiment we change the plasma displacement so as to investigate the effect of displacement on the reflection of LHW. It is seen that the movement of plasma horizontal displacement has little effect on the wave-plasma coupling and that during the whole process the reflection remains

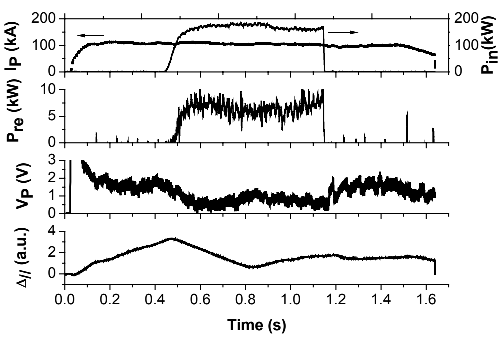

Fig. 5 Typical waveform of coupling experiments (#48003) (I_P: plasma current, P_{in}: injected LHW power, P_{re}: reflected LHW power, V_P: loop voltage, $\Delta_{//}$: plasma horizontal displacement)

very low (~5%), suggesting that the grill-mouth density does not vary so much to be below or close to the cut-off density. Despite the movement of plasma, the distance between the LCFS and the antenna aperture does not change during the displacement movement, for the LCFS is determined by the poloidal limiter that is fixed in our experiment. So, the density at the gill mouth changes little when the plasma moves inward and outward. Therefore, the plasma horizontal displacement has little effect on the wave-plasma coupling. As discussed in the above paragraph, since the density at the grill mouth satisfies the coupling condition, of course, it is reasonable that the reflection remains low during the whole discharge.

4. Analysis of Current Drive Efficiency

The power of current drive of the MJ antenna is also studied through investigating its current drive efficiency by scanning phase-difference ($\Delta\Phi = 60^0, 120^0$) between the adjacent waveguides, correspondingly, $N_{//}^{peak} = 2.7$ and 3.1, with different plasma density (n_e=1.0, 1.5, 2.0 (x$10^{19}m^{-3}$)). The experiments were performed with the parameters of I_p~150kA, I_t~1.9Tesla, and P_{LHW}~350kW. Figure 6 shows effects of the power spectrum and the plasma density on the current drive efficiency for present MJ grill. For a comparison, the dependence of current efficiency on plasma density with $N_{//}^{peak}$=2.9 for the traditional antenna, which has been studied in Ref. 11, is also displayed in the figure.

Same as the study of the traditional antenna, the experiments were performed with a feedback control system that adjusts the input power from the Ohmic (OH) transformer to keep plasmas current I_p as a constant. The current drive efficiency was evaluated by the formula [12],

$$\eta_{cd}^{\exp er} = \frac{n_e I_{rf} R_p}{P_{rf}} (10^{19}\mathrm{Am^{-2}W^{-1}}) \qquad (1)$$

where R_p is the major radius of tokamak and P_{rf} is the LH wave power absorbed by the plasma through Landau damping. The driven current I_{rf}, was approximated by $I_{rf} = \frac{\Delta V}{V_{OH}} \cdot I_p$, in which the Spitzer resistivity effect is neglected, where $\Delta V = V_{OH} - V_{LH}$, V_{OH} is the loop voltage in the OH heating phase just before the LHW application and V_{LH} is the loop voltage during LHCD phase.

It is seen that, for the cases of $N_{//}^{peak}$ =2.7 and 3.1, a best drive effect is obtained at the density of $1.5\times10^{19}m^{-3}$. Though the experiment data are very limited, comparison with the results of the traditional antenna shows that it is consistent that there is an optimized density region where good drive efficiency is obtained for the two launchers. Analysis [11] suggests that this is mainly dominated by the competition between wave accessibility condition and impurity concentration (Z_{eff}). High plasma density makes more wave

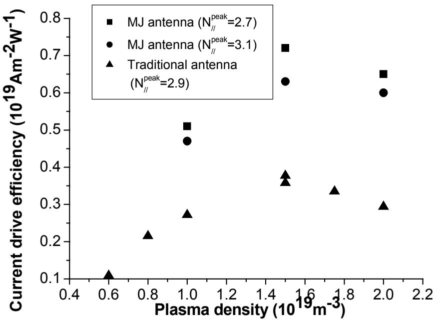

Fig. 6 Dependence of drive efficiency on density and spectrum

beams cannot go into the core plasma due to the accessibility condition and Z_{eff} increases in the case of low density. As a result, according to the theoretical formula derived from Fisch's theory [13],

$$\eta_{cd}^{theor} = 1240/[\ln \Lambda(5+Z_{eff}) < N_{//}^2 >] \quad (2)$$

with
$$\frac{1}{< N_{//}^2 >} = \frac{\int_{N_{//acc}}^{+\infty} P(N_{//})/N_{//}^2 dN_{//} - \int_{-\infty}^{-N_{//acc}} P(N_{//})/N_{//}^2 dN_{//}}{\int_{-\infty}^{+\infty} P(N_{//}) dN_{//}}, \quad (3)$$

it is only in an optimized density range where good drive efficiency is available, where $P(N_{//})$ is the power spectrum of the launched LHW, $N_{//acc}$ the critical value of parallel refractive index and Λ the parameter related to the plasma energy.

The efficiency difference at different $N_{//}^{peak}$ is mainly because the wave beams interact with the electron in the different region through Landau damping during their propagation because of their different phase velocity, for the values of Z_{eff} are almost equal for an identical plasma density and plasma temperature T_e. When $\Delta\Phi=60^0$, the corresponding $N_{//}$ is smaller, most of the wave beams interact with the core electrons with larger velocity. With the increasing $\Delta\Phi$, more LHW beams interact with the edge electrons, which is identified by the power deposition profiles in Fig. 7 calculated using the ray tracing code with $n_e=1.0\times10^{19}\text{m}^{-3}$, an electron temperature T_e =1.1keV deduced from a soft X-ray energy spectrum, B_t=1.9T, and I_p=150kA for the two spectra. It is seen that, compared to the case of $\Delta\Phi=120^0$, the deposition peak is nearer to the core region and the profile is peaker when $\Delta\Phi=60^0$, indicating that more wave energy is absorbed by the core electrons. Since the density and the temperature in the core plasma are higher than that in the edge region, of course, the drive efficiency in the $\Delta\Phi=60^0$ case is larger than that in the case of $\Delta\Phi=120^0$. This result demonstrates that the efficiency is greatly dependent on the power spectrum.

Further comparison shows that, in the whole density region, the drive efficiency for the MJ antenna is higher than that for the traditional one, indicating that the MJ grill is more effective to drive current than the traditional coupler. Simulations in section 2 shows that it is one of candidates for the difference of drive efficiency that the MJ coupler drives a smaller negative/counter-direction current fraction because of its more asymmetric spectrum, hence obtaining a larger total non-inductive current. Of course, this explanation may not account for

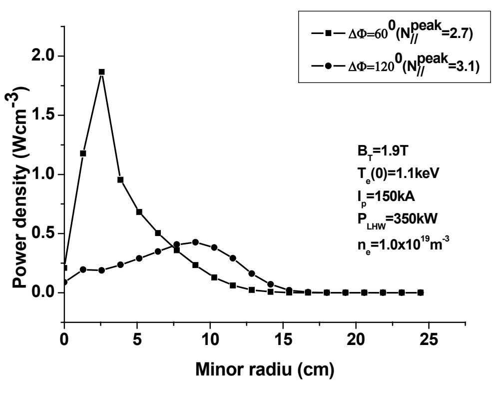

Fig. 7 Simulated power deposition

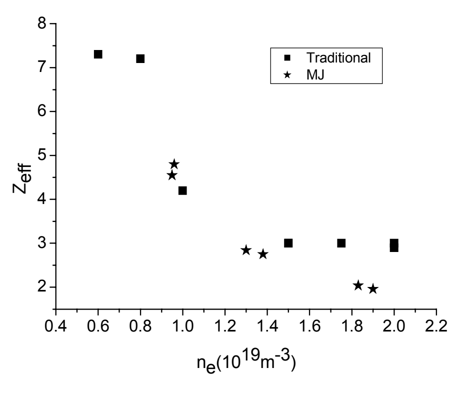

Fig.8 Dependence of Z_{eff} on n_e

the experimental discrepancy of the drive efficiency completely, for, as shown in Fig. 5, the efficiency of the MJ coupler is almost twice as that of the traditional one and simulation shows that the contribution from the negative current can not lead to so much difference. Other physics behavior in the discharge, such as impurity radiation, or electron temperature, could be also responsible for the large discrepancy of the driven efficiency. The obtained drive efficiency in JT-60, ASDEX and JET devices [14],

$$\eta_{CD} = \frac{T_e}{5 + Z_{eff}} C(N_{//}) , \qquad (4)$$

indicates that the drive efficiency strongly depends on impurity concentration and temperature, where $C(N_{//})$ is a parameter correlating with power spectrum. For the MJ antenna, the estimated values of Z_{eff} from the impurity radiation before the LHCD application are shown in Fig. 8, in which also shown are the values [11] for the traditional antenna. It is seen that in the low density region, the values are in line with the curve of the traditional antenna. Whereas with the density increase, they deviate from the original curve step by step and become smaller and smaller. It beneficiates to a higher efficiency in the high density region, but it does not so in the low density plasma. This means that, though Z_{eff} in the case of MJ grill is smaller than that in the case of the traditional one in the high density plasma, it is also only part of the candidates for the discrepancy of the drive efficiency. Since spectrum and impurity concentration can't explain the experiment results completely, according to equation (2) and (4), it is speculated that T_e may be another candidate for the higher drive efficiency, which is not taken into account in the Fisch's theory. Therefore, impurity concentration, plasma temperature and counter-direction driven current fraction contributed from the negative spectrum could be responsible for the different drive efficiency between the two launchers.

5. Conclusion

A phase-controlled LHW MJ coupler has been developed in the HT-7 tokamak. Simulations show that it is more effective to drive plasma current than a traditional coupler. Studies of the plasma and wave coupling experiment, performed by scanning plasma density and phase-difference between waveguides, show that good coupling efficiencies with low reflection coefficients below 10% are obtained. The spectrum scan experiment shows that an optimized spectrum is required for a better coupling. The density variation has little effect on the coupling. The movement of plasma displacement has little effect on the wave-plasma coupling and during the whole process the reflection remains very low (~5%). The low reflections suggest that the plasma density in front of the grill mouth satisfies the coupling condition. The little effect of plasma displacement on reflection is ascribed to the non-shifted LCFS determined by the fixed poloidal limiter in our experiments.

The investigations of the capability of current drive of the MJ antenna show that there is an optimized density region where good drive efficiency is obtained, which is mainly dominated by the competition between wave accessibility condition and impurity concentration. Studies of drive efficiency for different $N_{//}^{peak}$ indicate that the efficiency strongly depends on power spectrum. For a certain density, the drive efficiency for the MJ antenna is higher than that for the traditional one. Studies indicate that lower impurity concentration, higher plasma temperature and smaller counter-direction driven current fraction contributed from the negative spectrum could be responsible for the higher drive efficiency of the MJ coupler.

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