論文の内容の要旨

論文題目

A Study of Non-Inductive Plasma Current Start-Up Using the Lower Hybrid Wave in the TST-2 Spherical Tokamak

(TST-2 球状トカマクにおける低域混成波を用いた非誘導プラズマ電流立ち上げに関する研究)

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Radio frequency (RF) waves are used in many tokamak experiments for heating, current drive, and plasma start-up. RF and other non-inductive techniques play more important roles in spherical tokamaks (STs) compared to conventional tokamaks, because of the crucial need for eliminating the central solenoid. In conventional tokamaks, the lower hybrid wave (LHW) has demonstrated high efficiency for driving current [1]. Plasma start-up and current ramp-up to 100 kA has also been achieved [2]. Waves in ST plasmas behave very differently from those in conventional tokamak plasmas because of very high dielectric constants ($\sim \omega_{\rm pe}^2/\Omega_{\rm e}^2$) associated with the ability of the ST to confine high density plasmas at low magnetic fields. Although a deterioration of the current drive efficiency using the LHW is known to occur at high densities [3,4], an effective current drive should be possible if the LHW is utilized keeping the density low during the plasma current ramp-up phase. Therefore, in this thesis, the feasibility of plasma current start-up and ramp-up by the LHW to a sufficient level needed for further heating is investigated.

The 200 MHz RF power was utilized to excite the LHW in TST-2. This frequency is one order of magnitude lower compared with typical frequencies utilized for LHW in conventional tokamaks. Three types of antennas with distinctive features were used in this thesis: the (inductively-coupled) combline antenna, the dielectric-loaded waveguide array antenna (a.k.a. grill antenna), and the electrostatically-coupled combline antenna (ECC antenna).

Initial plasma start-up and plasma current ramp-up to 15 kA were achieved by the combline antenna but the current drive efficiency was lower than other antennas (cf. Fig. 1). The current drive efficiency could be improved by using the grill antenna and the ECC antenna which can excite the LHW with suitable polarization efficiently. The ability of the grill antenna to excite the LHW with different $n_{||} = ck_{||}/\omega$ was used to identify the most favorable $n_{||}$ spectrum for plasma current ramp-up. Based on the achieved plasma current and the energy spectrum of the emitted X-rays, it was found that effective current drive can be achieved by the LHW with $n_{||}$ less than 6 (cf. Fig. 2). However, even in this case, the energetic electrons which account for a large fraction of the driven current, are lost rapidly because the poloidal field generated by the plasma current is not sufficient to confine these electrons.

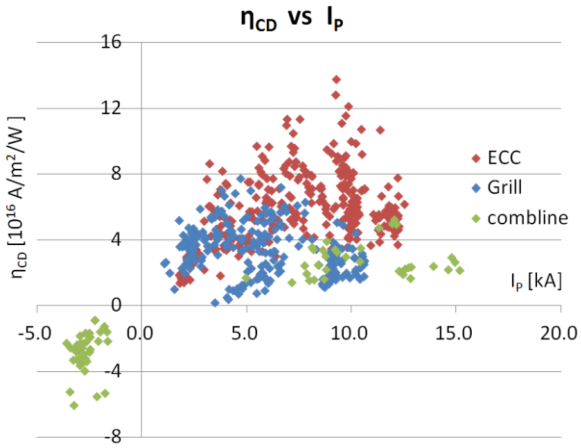
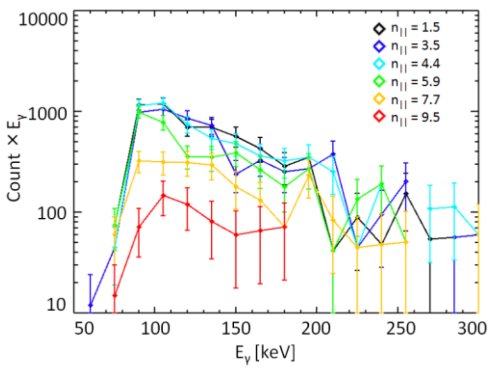


Figure 1. Comparison of the current drive figure of merit $\eta_{\mathrm{CD}} = \bar{n}_e R I_{\mathrm{p}} / P_{\mathrm{RF}}$ achieved with the three antennas (ECC, grill, combline) plotted versus the plasma current.

The antenna-plasma coupling of the grill antenna deteriorates as the input power exceeds several kW. This deterioration is believed to be caused by the density depletion due to the ponderomotive force. This hypothesis was confirmed experimentally and theoretically. The actual density depletion when the input power exceeded several kW

(a)



(b)

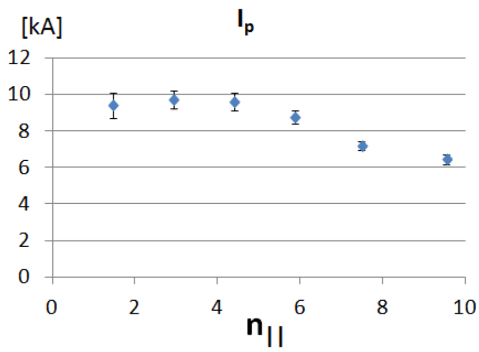


Figure 2. Comparison of hard X-ray spectra (a) and the plasma current (b) obtained for different $n_{||}$. The hard X-ray emission became weaker and the achieved plasma current decreased for $n_{||}$ greater than 6.

was measured by the electrostatic probe installed on the inner wall of the private limiter (cf. Fig. 3). The FEM antenna-plasma coupling simulation which takes into account the ponderomotive effect also shows the coupling deterioration due to density depletion. The reflection coefficient starts to increase at the same order of input power as in the experiment assuming the plasma temperature is 5 – 10 eV, which is consistent with the temperature measured by the mid-plane Langmuir probe.

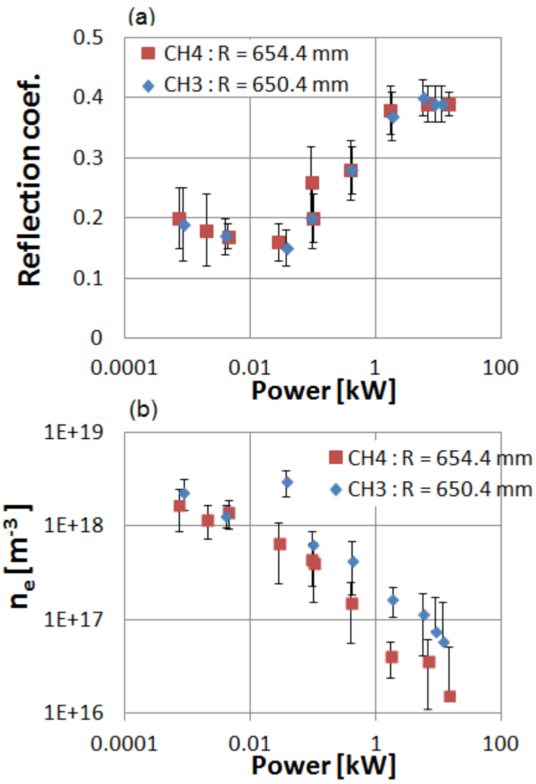


Figure 3. The dependences of the reflection coefficient and the electron density on the input RF power.

The ECC antenna overcame this problem because the coupling characteristics of this antenna are not as sensitive as the grill antenna. The highest current drive figure of merit was achieved using the ECC antenna. This is because the $n_{||}$ spectrum of the LHW launched by the ECC antenna has a sharper peak than the grill antenna. In addition, the $n_{||}$ spectrum of the grill antenna has the reverse going peak whose strength is one-third of the main peak while that of the ECC antenna is less than 5 %. These differences are the consequence of the difference in the number of antenna elements. The ECC antenna has 13 elements while the grill antenna has only 4 (cf. Fig. 4). Therefore, the ECC antenna can launch a better defined traveling wave than the grill antenna.

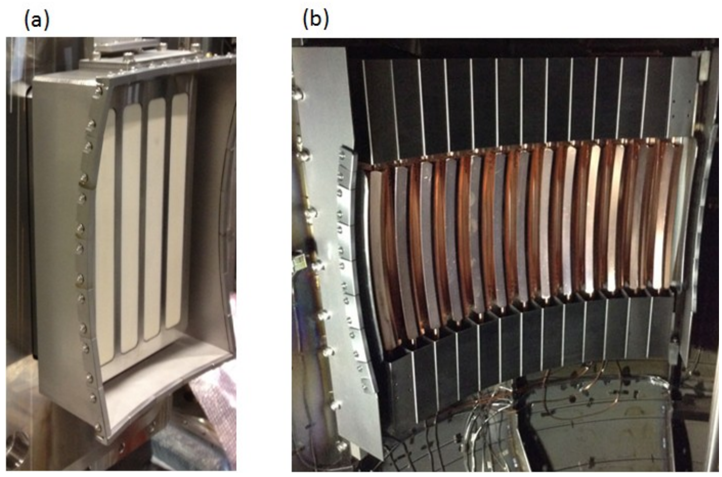


Figure 4. Photographs of the grill antenna (a) and the ECC antenna (b).

In this thesis, the feasibility of the plasma current start-up using the LHW was demonstrated by keeping the plasma density low. Although the difficulty in utilizing the grill antenna at low frequency such as 200 MHz was revealed, the noble ECC antenna was able to solve this problem and demonstrated the highest current drive efficiency on TST-2.

[1] S. Bernabei, et al., Physical Review Letters 49, 1255–1258 (1982).

[2] F. Jobes, et al., Physical Review Letters 52, 1005–1008 (1984).

[3] Y. Takase, et al., Physics of Fluids 28, 983 (1985).

[4] M. Mayberry, et al., Physical review letters 55, 829–832 (1985).