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X-ray measurements during non-inductive plasma current start-up experiments using lower hybrid waves on 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時のX線計測

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Non-inductive plasma current start-up experiments using RF power in the lower hybrid frequency range is being conducted on the TST-2 spherical tokamak. Plasma currents of up to 15 kA have been achieved. The effect of direct current drive can be seen by comparing the cases with co-drive and counter drive. X-rays with various energies were measured to investigate the interaction between the wave and electrons. Soft X-ray measurements imply that fast electrons driven by lower hybrid wave (LHW) have some contribution to the plasma current. However, the RF amplitude modulation experiments showed that the confinement time of these fast electrons seems to be very short (less than 0.1 ms) compared to the collisional slowing down time. Hard X-ray measurements showed that the effective temperature of fast electrons in co-direction for current drive was higher than that in counter direction. This fact confirmed the existence of RF driven fast electrons.

1. Introduction

Lower hybrid wave (LHW) has demonstrated high efficiency for driving current in conventional tokamaks [1]. If the plasma current can be ramped-up by LHW to a sufficient level that is needed for further heating (e.g. NBI), the central solenoid can be eliminated. However, waves in spherical tokamak plasmas behave very differently from those in conventional tokamak plasmas because of very high dielectric constants ($\sim \omega_{pe}^2/\omega_{ce}^2$), which arises from the high density at low magnetic field ST plasmas. In addition, deterioration of the lower hybrid current drive (LHCD) efficiency is known to occur at high densities [2][3]. Therefore, it is very important to demonstrate the feasibility of a plasma start-up scenario using the LHW in ST.

LHW is thought to be absorbed by high energy electrons through Landau damping. Therefore, X-ray measurements were performed to measure bremeetrahlung of high energy electrons. The main interest is to confirm the existence of RF driven fast electrons and its contribution to the plasma current.

2. TST-2 spherical tokamak

TST-2 spherical tokamak is a small size spherical tokamak placed at the University of Tokyo. The major radius R_0 = 0.35 m, the minor radius a = 0.23 m, and the toroidal field B_T = 0.1 T. The plasma current ramp-up to 15 kA was successfully achieved at TST-2 by LHCD with a slow vertical field ramp-up.

LHW is excited in TST-2 by the antenna so-called “combline antenna”. This antenna is originally designed for excitation of travelling fast wave at 200 MHz. However, the wave excitation simulation using a versatile finite element method solver package COMSOL predicts that the slow wave (which is LHW) can be excited in the condition of this experiment. This is because the fast wave is cutoff for the density we consider. The parallel refractive index of excited LHW $n_{\parallel}$ = 7.2 at the edge. The injected power is up to 150 kW, but injected power to the plasma is less than 70 kW and the remaining is transmitted to output port.

As shown in Fig. 1, the plasma current is nearly proportional to the applied vertical field. The direction of plasma current inverts with the reversal of vertical field direction. The negative value means the plasma current flows in counter direction against LHCD. In counter drive case, the magnitude of plasma current cannot exceed 4 kA. This fact reflects the effect of direct current drive by LHW is important in this experiment especially higher current case.

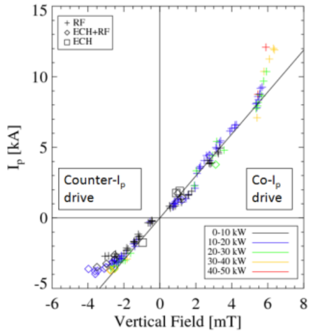

Fig. 1. The plasma current dependency on vertical field strength. Negative value denotes counter drive case by LHCD. The data which divert from proportionality in co-drive case require higher filling pressure than others.

3. X-ray measurements

3.1 *Soft X-ray measurements*

The dependence of the perpendicular (i.e., along the major radius) soft X-ray (SX) emissions on the plasma current was investigated. The higher energy SX in energy range 1-10 keV significantly increased as the plasma current increased. This fact suggests that fast electrons produced by LHW have some contributions to the plasma current.

Hard X-ray (HX) emission is measured by NaI scintillator in two tangential viewing chords. One chord is oriented to detect HX emitted from co-driven fast electrons and the other chord is oriented to detect those from counter driven electrons. Build up of HX emission was observed as the plasma current increased. HX from co-driven electrons is always stronger than that from the other. At the current flat top, a slight difference in effective temperature of fast electrons can be seen.

The RF amplitude modulation (AM) experiments were performed in order to investigate fast electron confinement. We varied AM frequency from 0.2 kHz to 3 kHz. The phase of lower energy SX (whose energy was in the range 10-70 eV) started to delay at 0.5 kHz while the phase delay of higher energy SX (whose energy is in the range 1-10 keV) was not observed. We consider a simple model for

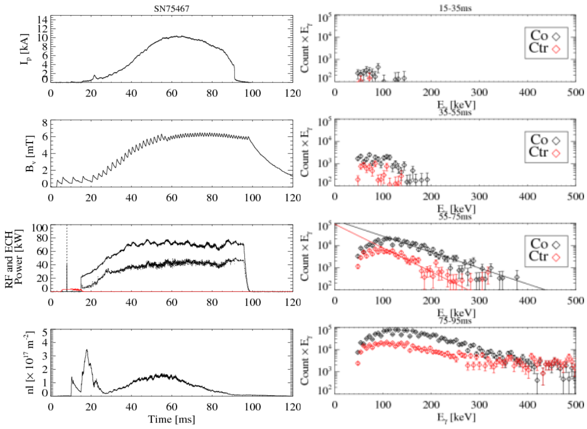

Fig. 2. The time evolution of HX spectrum (right figure) and correspond discharge waveform. The black and red symbols represent energy spectrum of HX in co-direction and counter direction, respectively. The lines in 3rd figure show the effective temperature of fast electrons.

the population of high energy electrons as Eq. 1.

$$\frac{\partial n_H}{\partial t} = -\frac{n_H}{\tau_H} - \frac{n_H}{\tau_{loss}} + S_0 e^{i\omega t}, \qquad (1)$$

where n_H is the density of high energy electrons, τ_H is the slowing down time, τ_{loss} is typical time scale of loss term, S_0 is magnitude of RF source term and ω is AM frequency. Solving this equation, the relative phase of high energy electron density can be written as

$$\phi_H = \mathrm{Arctan}(-\omega\tau') \qquad (2)$$

where,

$$\tau' = \frac{\tau_H \tau_{loss}}{\tau_H + \tau_{loss}}. \qquad (3)$$

If $\tau_H \ll \tau_{loss}$, τ' falls on the same order of τ_H, however, the slowing down time of high energy electrons is longer than that of low energy electrons, thus higher energy SX should start to delay at lower frequency than lower energy SX. Therefore, the rapid loss term should be present and its timescale is less than 0.1 ms. This rapid loss of fast electrons can be attributed to the orbit loss. The orbit drift size of 10 keV fast electrons is approximately 30 mm, thus observed fast electrons may reside mainly near the edges.

Acknowledgments

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References

[1] S. Bernabei, et al., Physical Review Letters **49**, 1255–1258 (1982).
[2] Y. Takase, et al., Physics of Fluids **28**, 983 (1985).
[3] M. Mayberry, et al., Physical review letters **55**, 829–832 (1985).