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# Non-inductive current start-up experiments using the Lower Hybrid Wave on the TST-2 Spherical Tokamak

# TST-2球状トカマク装置における低域混成波を用いた非誘導電流立ち上げ実験


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Plasma current ($I_p$) was successfully non-inductively started and ramped up to 16 kA, by the lower hybrid wave (LHW) and the electron cyclotron wave (ECW) on TST-2. The LHW was excited by the capacitively-coupled combline (CCC) antenna. The current drive efficiency was a factor of two higher for the CCC antenna compared to antennas used previously. The maximum $I_p$ was found to increase linearly with the toroidal magnetic field ($B_t$).


## 1. Introduction

Very high $\beta$ plasmas have been achieved in spherical tokamak (ST) plasmas due to its low aspect ratio and strong shaping [1]. However, it is challenging to realize a compact burning ST fusion reactor without eliminating the central solenoid, which is normally used for inductive current drive. Highly efficient non-inductive plasma current ($I_p$) start-up and ramp-up by the lower hybrid wave (LHW) is already demonstrated in conventional tokamaks. For example, $I_p$ ramp-up by the LHW, leading to an advanced tokamak discharge with near unity bootstrap current fraction, was achieved on the JT-60U tokamak [2]. Conversely, it is generally believed that current drive by the LHW is not possible in ST plasmas. The objective of this work is to study and demonstrate $I_p$ ramp-up by the LHW on the TST-2 spherical tokamak [3].

## 2. LHW Antennas on TST-2

In previous experiments on TST-2, the inductively-coupled combline (ICC) antenna (fast wave antenna, 11 elements) and the dielectric-loaded grill antenna (LHW antenna, 4 elements) were used for $I_p$ start-up experiments at 200 MHz [3,4]. These experiments suggested that a new antenna which excites the LHW directly with high directionality and sharp $n_{\parallel}$ (refractive index along the magnetic field) spectrum. The CCC antenna was designed to satisfy these requirements, and is now used on TST-2 [3].

The CCC antenna (LHW antenna, 13 elements) excites the LHW (200 MHz) directly utilizing capacitive coupling between adjacent elements of the antenna. To obtain high directionality and sharp $n_{\parallel}$ spectrum, the CCC antenna uses 13 antenna elements. RF power is gradually radiated into the plasma as it propagates through 13 elements of the antenna. In order to excite a sharp $n_{\parallel}$ spectrum, approximately 10% of the incident RF power must remain at the last (13th) element.

## 2. Experimental Setup

In this experiment, the CCC antenna was used. Magnetic probes are used to measure RF power and phase at selected elements of the antenna, from which the $n_{\parallel}$ spectrum of the excited LHW can be calculated. Toroidal magnetic field ($B_t$) of up to 0.12 T was used. The line integrated density ($n_e l$) along a vertical chord through the nominal center of the plasma ($R$ = 0.38 m) was measured by a microwave interferometer.

## 3. Results of the $I_p$ Start-up Experiment

$I_p$ was non-inductively ramped up to 16 kA by the LHW (~30 kW) and the ECW (~5kW). This is a record for TST-2 non-inductive plasmas. 10% of the input RF power remained at the 6-7th element due to strong radiation into the plasma. The width of the excited $n_{\|}$ spectrum is about half as wide as the grill antenna. The current drive figure of merit ($\eta_{CD} = I_p \langle \bar{n}_e \rangle R_0 / P_{RF}$, where $\langle \bar{n}_e \rangle = n_e l / 0.5$) achieved by the CCC antenna is a factor of two higher than that obtained by the ICC and the grill antennas, as shown in Fig. 1 (a). As shown in Fig. 1(b), the maximum $I_p$ was found to depend linearly on $B_t$ as $I_p$ [kA] = 148$B_t$ [T] – 0.5.

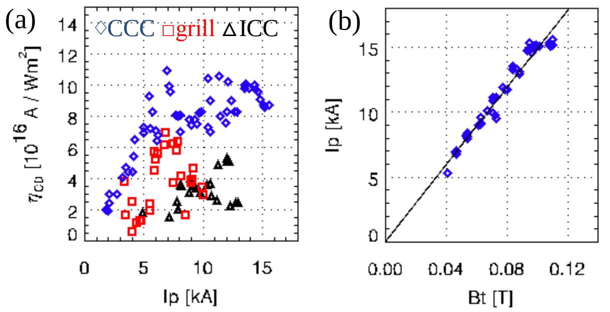


Fig. 1. (a) $\eta_{CD}$ obtained using CCC (diamond), grill (square), ICC (triangle) antennas. (b) Correlation between maximum $I_p$ and $B_t$.

## 3. Discussion and Conclusions

Non-inductive $I_p$ start-up and ramp-up to 16 kA by the LHW was achieved successfully using the CCC antenna. The $n_{\|}$ spectrum of the excited LHW was broader than the optimum case because of strong antenna-plasma coupling, but it is approximately half as wide as that of the grill antenna. In order to excite a sharper $n_{\|}$ spectrum, it is necessary to reduce the plasma density in front of the antenna to weaken antenna-plasma coupling.

The current drive efficiency achieved using the CCC antenna was a factor of two to three higher than that obtained using the ICC antenna or the grill antenna, presumably because of direct LHW excitation with good directionality and a narrow $n_{\|}$ spectrum.

The maximum $I_p$ was found to increase linearly with $B_t$. The physical mechanism should be investigated to reach higher $I_p$. Generally, higher $B_t$ improves accessibility of the LHW to the plasma core. The accessibility condition can be derived from the cold plasma dispersion relation [5] as

$$|n_{\|}| \geq n_a = \omega_{pe} / \omega_{ce} + \sqrt{\varepsilon_{\perp}}\,, \qquad (1)$$

where $\omega_{pe}{}^2 = n_e q^2 / \varepsilon_0 m_e$, $\omega_{pi}{}^2 = n_i q^2 / \varepsilon_0 m_i$, $\omega_{ce} = qB / m_e$, and $\varepsilon_{\perp} = 1 + (\omega_{pe}/\omega_{ce})^2 - (\omega_{pi}/\omega)^2$. The value of $n_a$ is evaluated using the measured $B_t$ and $\langle \bar{n}_e \rangle$ at $R$ = 0.38 m. Figure 2 (a) shows the nearly inversely proportional dependence of the experimentally achieved $I_p$ on calculated $n_a$. The $n_{\|}$ spectrum of the excited LHW is shown in Fig. 2 (b). In order to satisfy the accessibility condition for $n_{\|} = -2$, $B_t$ must be increased up to 0.15-0.2 T.

As future work, the change of $n_{\|}$ due to toroidal geometry magnetic field shear must be taken into account for accessibility analysis. This effect is important for ST because $n_{\|}$ can change dramatically due to high toroidicity. We will calculate ray-tracing code will be used to study this effect. Furthermore, RF power deposition profile, the velocity distribution function, and the driven current density profile will be calculated using a Fokker-Planck code. Results of these studies will be used to evaluate the required $B_t$ to reach higher levels of $I_p$ (50-100 kA) in TST-2.

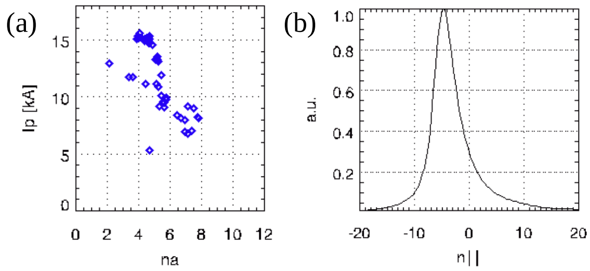


Fig. 2. (a) $I_p$ versus $n_a$. (b) $n_{\|}$ spectrum of CCC antenna, as measured by magnetic probes.

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## References

[1] M. Gryaznevich et al., Phys. Rev. Lett. **80**, (1998) 3972.
[2] Y. Takase et al., J. Plasma Fusion Res. **78**, (2002) 8.
[3] Y. Takase et al., Nucl. Fusion **53**, (2013) 063006.
[4] T. Wakatsuki et al., Nucl. Fusion **54** (2014) 093014.
[5] T. H. Stix, *Waves in Plasmas*, (Springer, New York, 1992).