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Plasma Current Start-up by the Lower Hybrid Wave in the TST-2 Spherical Tokamak

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Because of its high β capability, the low aspect ratio spherical tokamak (ST) is a promising candidate for a next generation fusion nuclear science facility or a fusion pilot plant. If the ST can be operated without a central solenoid, the feasibility of this approach improves dramatically. This work aims at demonstrating and improving the efficiency of non-inductive plasma current start-up and ramp-up in ST by RF power in the lower hybrid frequency range.

On the TST-2 spherical tokamak (with typical parameters: R = 0.36 m, a = 0.23 m, B_t = 0.3 T, I_p = 0.1 MA), plasma current start-up by the lower hybrid wave (LHW) at 200 MHz is being investigated [1]. Up to 400 kW of RF power is available. An innovative antenna called the capacitively-coupled combline (CCC) antenna was developed to excite a sharp, highly directional traveling wave with the electric field polarized in the toroidal direction. It is an array of resonant circuit elements made of capacitance and inductance, coupled to neighboring elements by mutual capacitance. Two CCC antennas are installed in TST-2, a 13-element outboard-launch antenna and a 6-element top-launch antenna (Figure 1). The latter was installed in March 2016 to improve accessibility of the LHW to the core and to achieve strong single-pass damping.

The outboard-launch CCC antenna installed in 2013 had a 100% antenna-plasma coupling efficiency and high power handling capability. A fully non-inductive plasma current start-up and ramp-up to 25 kA was achieved using this antenna (Figure 2), which is a significant fraction of the typical plasma current of 60-100 kA for inductive operation. Although it is desirable to keep the density low during the current ramp-up phase to avoid the density limit, it is found that the driven plasma current actually increases almost linearly with the density. However, in order to reach higher plasma currents, the toroidal field must be increased to avoid the density limit. A ray-tracing based numerical analysis of lower hybrid current drive in TST-2 showed that there is an optimum density for efficient current drive determined by the balancing of current drive saturation at low density and LHW diffraction at high density. This optimum density as well as the driven current increases with the toroidal field. The achievable plasma current with the outboard-launch CCC antenna is limited by the maximum toroidal field of TST-2.

In order to circumvent this problem and improve the current ramp-up efficiency, the top-launch CCC antenna was installed in 2016. Top-launching is advantageous because (1) the rays tend to propagate towards the plasma center even in high density plasmas, (2) the rays experience a large up-shift in the parallel index of refraction $n_\parallel$ during propagation, which improves wave accessibility to the core and strong Landau damping in the core, and (3) the loss of wave power in the scrape-off layer (SOL) plasma is avoided because the wave power is absorbed before the rays reach the SOL.

Initial experiments with the top-launch CCC antenna alone demonstrated formation of an ST plasma, but it was found difficult to control the plasma size and vertical position during the early start-up phase. In order to increase reliability of start-up, both antennas are now being used. Increase in the density limit was observed with the addition of the top-launch CCC antenna, as predicted theoretically.

References
[1] T. Shinya, et al., Nucl. Fusion 55 (2015) 073003.
[2] T. Shinya, et al., Nucl. Fusion 57 (2017) 036006.

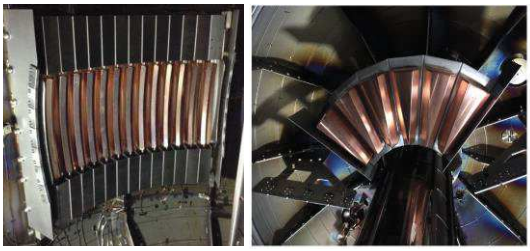

Figure 1. Photographs of the outboard-launch antenna (left) and the top -launch antenna (right).

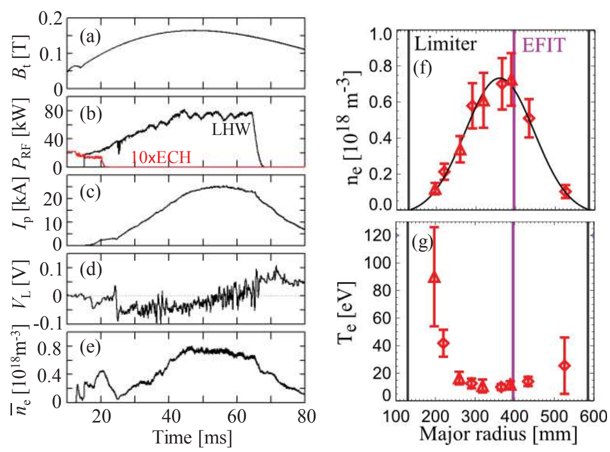

Figure 2. Waveforms of (a) Bt, (b) net RF (LH and EC) powers PRF, (c) Ip, (d) loop voltage VL, (e) line-average density ne, (f) and (g) electron density and temperature profiles measured by Thomson scattering at 55 ms.