Development of a Plasma Current Ramp-up Technique for Spherical Tokamaks by the Lower-Hybrid Wave

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Abstract. Spherical tokamaks (STs) have the advantage of superior stability at high beta, but to realize a compact fusion reactor, the central solenoid (CS) must be eliminated. The plasma current could be maintained mainly by the self-driven current during the steady-state burning phase, but there is no established method of non-inductive current ramp-up from zero to a high enough level required for fusion burn. The lower-hybrid wave (LHW) is commonly used in tokamaks, but this technique is believed to be unusable in ST plasmas with very high dielectric constant. Wave excitation, propagation and damping were evaluated by numerical modeling for the TST-2 spherical tokamak (R = 0.68 m, a = 0.25 m, B = 0.3 T, I = 100 kA). Wave excitation is calculated by the RF antenna simulation tool based on the finite element method (COMSOL). The plasma is modeled as a medium with cold plasma dielectric response and artificially enhanced loss. Excitation of a traveling fast wave (FW) by the TST-2 combline antenna was confirmed by COMSOL calculation. However, the FW must be mode converted to the LHW to achieve efficient current drive. The TORLH full-wave solver, which can treat diffraction effects properly, was applied to the TST-2 LH current drive experiment. It is shown that core current drive by LHW is possible in the low density, low current plasma formed by ECH. It is important to keep the density low during current ramp-up, and the wavenumber must be reduced as the current increases in order to maintain core current drive. The results of these calculations and the initial experiment on TST-2 will be used to design an optimized LHW antenna with appropriate polarization and wavenumber spectrum controllability for the current ramp-up experiment. Taking a conservative value for the current drive figure of merit, the steady-state driven current by 200 kW of RF power is estimated to be 150 kA, which should be adequate for evaluating the usefulness of this technique up to a current level of 100 kA in TST-2. This technique should be usable during the low-density, low-current, non-burning start-up phase of a reactor to reach a sufficient current level needed for further heating. Initial results from the TST-2 experiment demonstrated that initial current formation and ST equilibrium formation can be achieved by RF power in the LH frequency range. Further current ramp-up by directly excited LHW will be investigated on TST-2. The success of the TST-2 experiment would provide a scientific basis for quantitatively evaluating the required CS capability for a low aspect ratio reactor.

1. Introduction

Spherical Tokamaks (STs) have the advantage of superior stability at high β, but to realize a compact fusion reactor or volumetric neutron source at low aspect ratio ($A = R/a \leq 2$), the central solenoid (CS) must be eliminated [1,2]. During the steady-state burning phase, the plasma current (I_p) could be maintained mainly by the self-driven current, with a small non-inductive current drive assist (e.g., NBCD). However, there is no established method of I_p ramp-up from zero to a high enough level required for fusion burn. The lower-hybrid wave (LHW) has been shown to accomplish this role in JT-60U [3], but this technique is believed to be unusable in STs with very high dielectric constant ($\omega_{pe}^2/\omega_{ce}^2 >> 1$). In this paper, LHW excitation, propagation and damping were evaluated by numerical modeling for the TST-2 spherical tokamak with $R \leq 0.38$ m, $a \leq 0.25$ m ($A \geq 1.5$), $B_t \leq 0.3$ T [4], and it is shown that LHW core absorption and current drive are possible in the low density, low current plasma formed by ECH. This technique should be usable during the low-density, low-current, non-

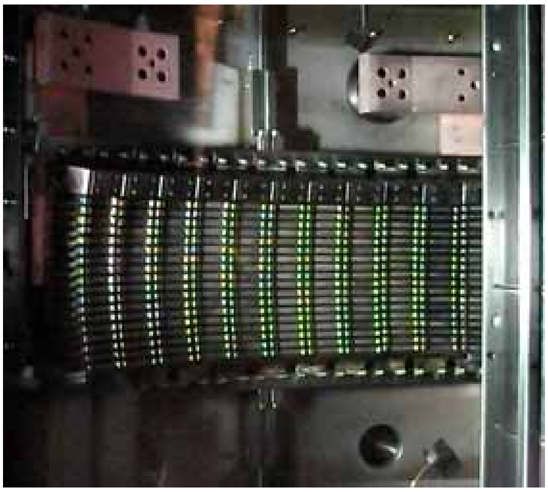

FIG. 1. The combline antenna installed inside the TST-2 vacuum vessel. Feeders can be seen above the combline antenna. RF power is fed to one of the end elements, propagates to neighboring elements by mutual induction while exciting waves in the plasma, and the remaining power exits from the other end element.

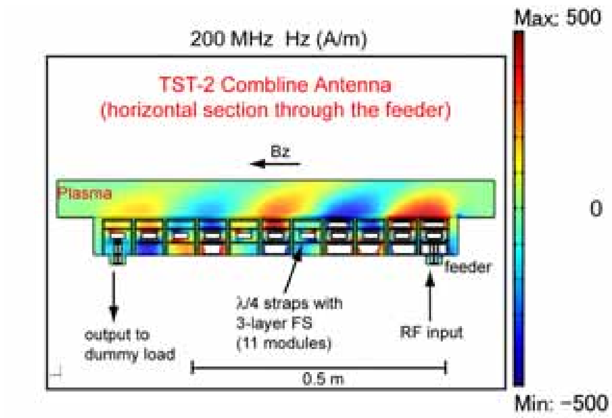

FIG. 2. Wave field (H_ϕ component) excited by the TST-2 combline antenna. RF power is fed to the rightmost element. B_t = 0.3T, $n_e = 1 \times 10^{18}$ m^{-3} (uniform density).

burning start-up phase of a reactor to reach a sufficient I_p level needed for further heating. In TST-2 up to 400 kW of RF power at 200 MHz can be supplied by four transmitters. Initially, the travelling-wave fast wave (FW) antenna (combline antenna) [5] will be used (Fig. 1). The results of this initial experiment and calculations presented here will be used to design an optimized LHW antenna with appropriate polarization and wavenumber spectrum controllability for the I_p ramp-up experiment. The success of the TST-2 experiment would provide a scientific basis for quantitatively evaluating the required CS capability for a low-aspect-ratio reactor.

2. Modelling of Wave Excitation

Wave excitation is modeled by the RF antenna simulation tool based on the finite element method (COMSOL) [6]. The combline antenna is modeled as 9 passive vertically oriented λ/4 straps and 2 active straps (rightmost and leftmost elements), as shown in Fig. 2. The power is fed to the rightmost element and excites neighboring elements by mutual induction. The toroidal and poloidal curvatures of the antenna are ignored for simplicity. The plasma is modeled as a medium with cold plasma dielectric response and artificial loss. This is adequate for evaluating antenna-plasma coupling and initial wave excitation. Figure 2 shows the toroidal component of the wave magnetic field (H_ϕ) on the

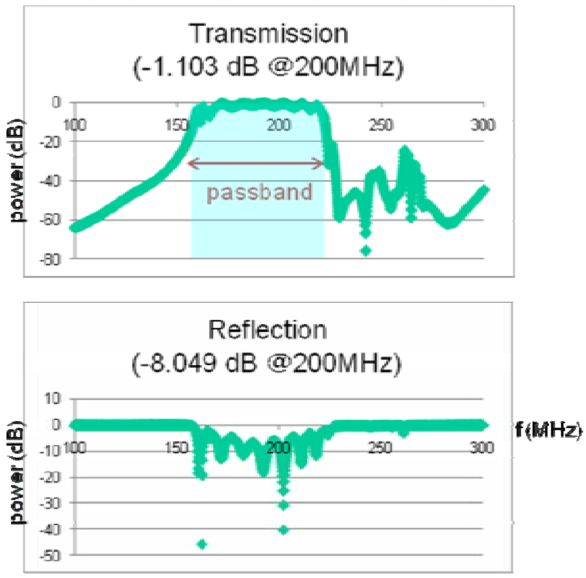

FIG. 3. Frequency response of the TST-2 combline antenna in vacuum. The antenna transmits frequencies in the range 160 to 220 MHz.

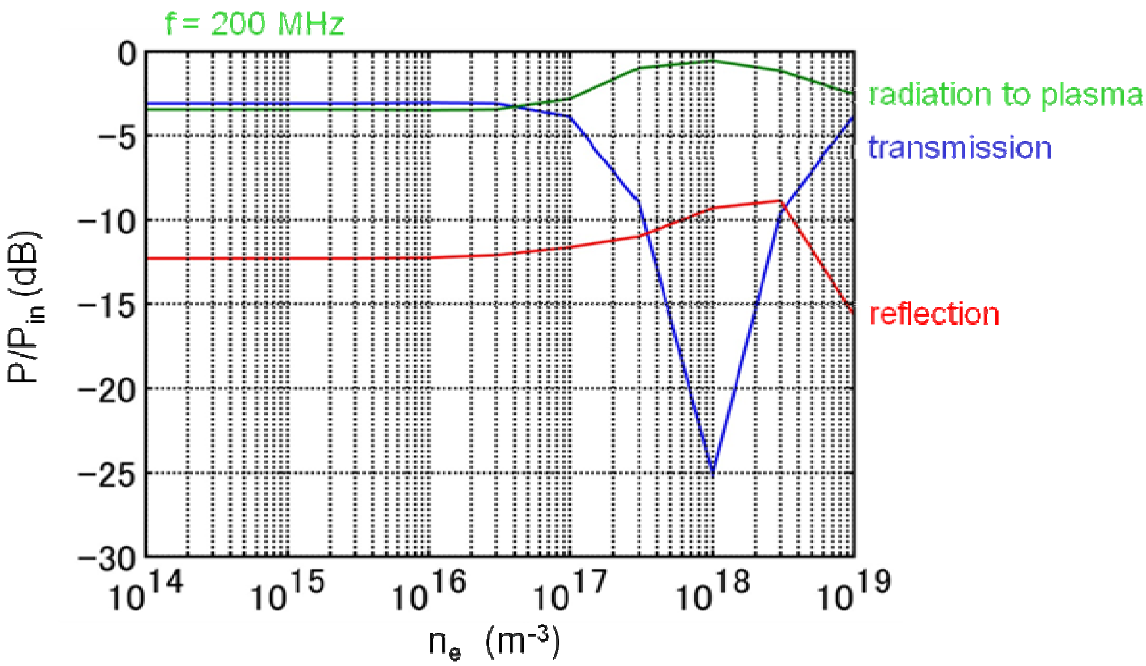

FIG. 4. Fractions of the power radiated to the plasma, transmission to the output port (into the dummy load), and reflection from the input port as functions of the electron density, calculated by COMSOL. The radiated power to the plasma maximizes at $n_e = 1 \times 10^{18}$ m^{-3}.

horizontal plane through the antenna feeders. Excitation of the leftward (and outward) moving fast wave can be seen clearly. This wave field is identified as the fast wave based on the polarization (dominant components being E_θ and H_ϕ) and the wavelength.

The combline antenna has the characteristics of a bandpass filter [7]. The frequency response of the TST-2 combline antenna is shown in Fig. 3. In the presence of plasma load, a fraction of the RF input power is radiated into the plasma, and the transmitted power is reduced. The efficiency of wave excitation, expressed by the radiation to the plasma normalized by the RF input power, is plotted as a function of electron density in Fig. 4. Reflection from the RF input port and transmission to the output port (into the dummy load) are also shown. Radiation to the plasma is maximized at a density of $n_e = 1 \times 10^{18}$ m^{-3}. At this density, the transmitted power becomes negligibly small.

The fast wave must be mode converted to the LHW to achieve efficient current drive. The dispersion relation across the plasma midplane is shown for three different densities in Fig. 5. For this particular choice of $n_{||}$, the LHW and the FW solutions are well separated, and no conversion occurs at $n_{e0} = 2 \times 10^{18}$ m^{-3}. At $n_{e0} = 5 \times 10^{18}$ m^{-3}, the LHW and FW solutions coalesce, and conversion between the two modes becomes possible. However, the lower hybrid resonance layer appears in the plasma core region. The LHW can exist only on the low field side of the resonance. Nonlinear effects such as parametric decay, and possibly ion heating by the mode converted ion plasma wave are expected to occur under such a condition. These effects are known to degrade the efficiency of current drive. At still higher density, $n_{e0} = 1 \times 10^{19}$ m^{-3}, the evanescent region, where neither LHW nor FW can propagate, occupies a large fraction of the plasma cross section, and waves can exist only on the outboard side.

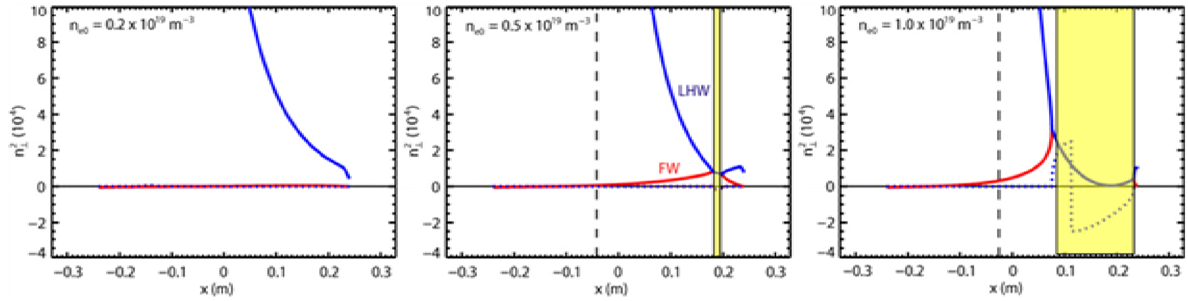

FIG. 5. Dispersion relation across the midplane for $n_{e0} = 2 \times 10^{18}$ m^{-3}, 5×10^{18} m^{-3}, and 1×10^{19} m^{-3} (from left to right). f = 200 MHz, B_t = 0.3 T, I_p = 100 kA, T_{e0} = 200 eV, toroidal and poloidal mode numbers n = 12, m = 0 (corresponding to $n_{||}$ = 4.8 @ R = 0.6 m). $n_\perp^2$ is plotted as a function of x = R – R0. The yellow shaded region corresponds to the evanescent region. The vertical dashed line indicates the location of the LH resonance layer.

3. Modelling of Wave Propagation and Excitation

The TORLH (formerly known as TORIC-LH) full-wave solver [8] was applied to the TST-2 LHCD experiment. TORLH can treat diffraction, which cannot be treated by ray-tracing codes. In this paper, TORLH calculations were done using Maxwellian velocity distribution function to evaluate damping. Enhanced damping due to the quasilinear deformation of the distribution function is simulated by increased electron temperature. A more proper treatment is to use quasilinearly deformed distribution function calculated by a Fokker-Planck code such as CQL3D. Iteration between TORLH and CQL3D is required to arrive at a self-consistent solution. This work is in progress. In Fig. 6 the logarithmic profiles of $|E_z|$ (wave electric field component along the magnetic field, which is relevant for electron Landau damping) are plotted for different I_p, for the low density ($n_{e0} = 1 \times 10^{17}$ m^{-3}) condition expected for the EC start-up plasma [9]. The antenna is located on the outboard midplane of

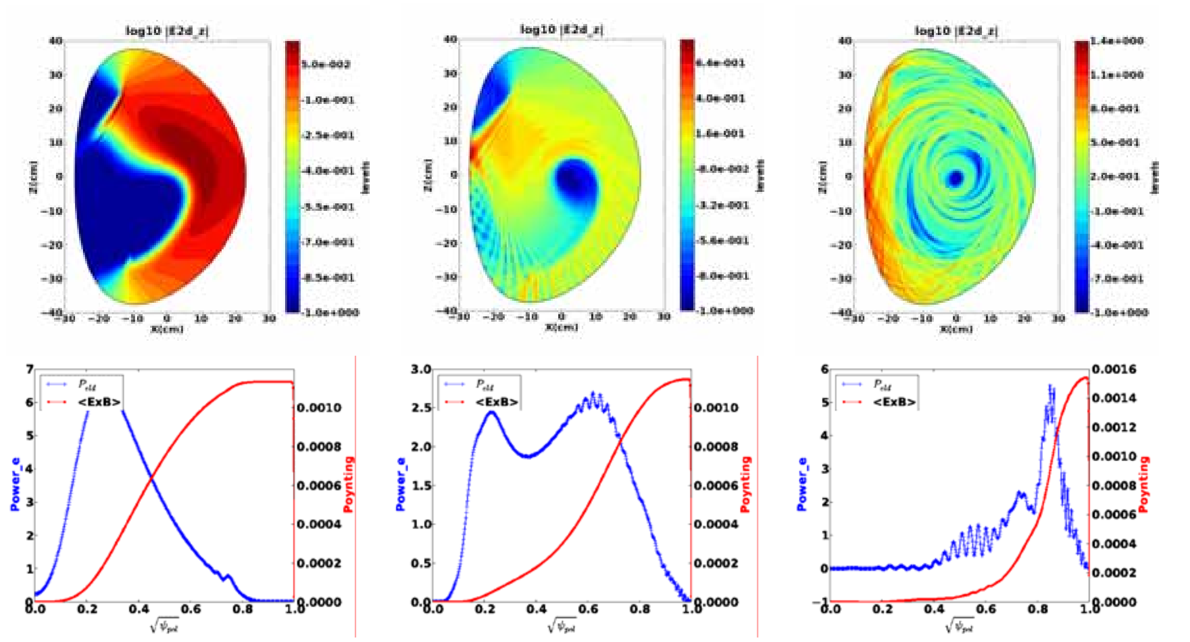

FIG. 6. Upper frames show the parallel electric field profiles log10$|E_z|$ for I_p = 10 kA (left), 30 kA (center), 100 kA (right), $n_{e0} = 1 \times 10^{17}$ m^{-3}, T_{e0} = 1 keV (effective temperature taking nonthermal electrons into account), B_t = 0.3 T, $n_{||0}$ = 7. Lower frames show the radial profiles of power absorbed by electrons, and the Poynting flux.

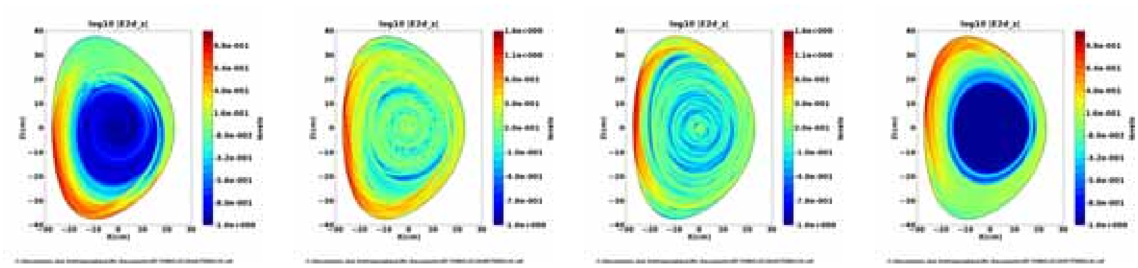

FIG. 7. Parallel electric field profiles log10|E_z| for $n_{||0}$ = 7, 3, -3, -7 (from left to right). $n_{e0} = 1 \times 10^{18}$ m^{-3}, T_{e0} = 1 keV, B_t = 0.3 T, I_p = 100 kA.

the torus. At low I_p immediately after plasma formation (10 kA), the LHW penetrates radially into the plasma, and is absorbed in the plasma core. However, as I_p increases, the parallel wavenumber increases due to the increasing magnetic shear. The shorter wavelength structure, the poloidal wave propagation, and peripheral wave absorption are all consequences of this effect. This may be useful for developing negative magnetic shear plasmas with strong internal transport barrier and well-aligned self-driven current profile. The TST-2 combline antenna can excite a travelling wave spectrum with a peak at n_ϕ = 18, which corresponds to $n_{||0}$ = 7 used for Fig. 6. Wave accessibility to the core and absorption in the core plasma can be recovered by reducing $n_{||0}$ as shown in Fig. 7. At this density and plasma current, wave fields are excluded from the plasma core for $n_{||0} = \pm 7$, but access to the plasma core becomes possible for $n_{||0} = \pm 3$. Note the asymmetry with respect to the sign of $n_{||0}$ because of the finite poloidal field. The dependence on plasma density was also studied, since it may be impractical to keep the plasma density low enough during I_p ramp-up. At $n_{e0} = 1 \times 10^{18}$ m^{-3}, the wave no longer penetrates to the plasma core and is absorbed in the peripheral region. At $n_{e0} = 5 \times 10^{18}$ m^{-3}, the lower hybrid resonance layer appears in the plasma core region, as discussed in Sec. 2.

The results presented above were obtained for a single toroidal mode number *n*. In reality the antenna excites a spectrum of mode numbers. In axisymmetric geometry such as tokamaks and STs, *n* is conserved. A three dimensional wave field distribution is constructed by summing the solutions for different *n*, with weighting corresponding to the spectrum excited by the antenna. An example is shown in Fig. 8. Isosurfaces of constant E_z are plotted. Helical wave trajectories can be seen, with concentrated wave fields in the lower inboard region.

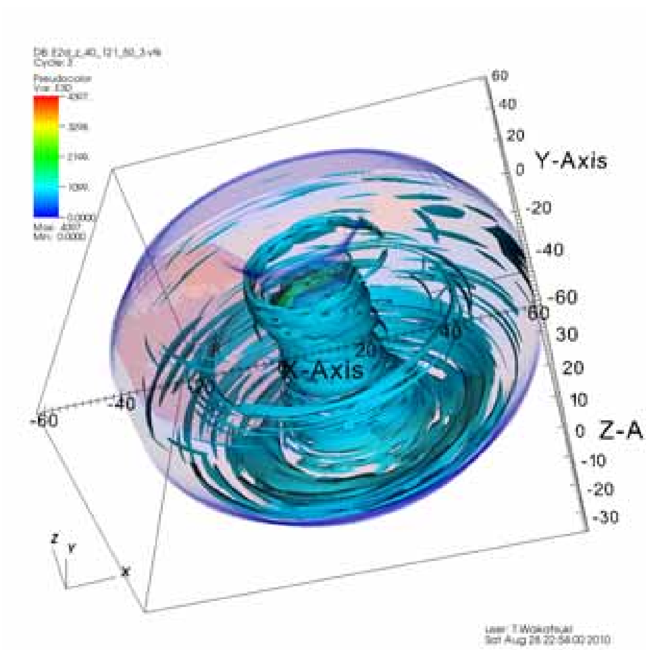

FIG. 8. Three dimensional wave field (E_z) distribution obtained by superposing toroidal mode numbers 11 ≤ n ≤ 21. B_t = 0.3T, I_p = 100 kA, $n_{e0} = 1 \times 10^{18}$ m^{-3}, T_{e0} = 200 eV.

The RF driven current was estimated using the current drive figure of merit, which is conservatively assumed to be n_e I_p R_0/P_{RF} = 1×10^{18} m^{-2} kA/kW.

The steady-state driven current by 200 kW of RF power at $n_e = 5 \times 10^{17}$ m^{-3} is estimated to be I_p = 150 kA, which should be adequate for evaluating the usefulness of this technique up to a current level of 100 kA (full current for TST-2). As mentioned earlier, iteration with CQL3D to evaluate damping self-consistently is in progress.

4. Initial TST-2 Experiment

Initial results are being obtained from the TST-2 experiment. Earlier results of plasma start-up using RF power at 2.45 GHz (ECH) and 21 MHz have been reported elsewhere [10, 11]. An ST configuration with closed flux surfaces is formed spontaneously by applying RF heating power at either frequency. It was shown recently that a similar result is obtained with RF power at 200 MHz [12]. In this section, initial results obtained with directional wave excitation using the combline antenna at 200 MHz are presented.

Time evolutions of two discharges with co current drive and counter current drive are shown in Fig. 9. Preionization by ECH is used, but ECH power is turned off prior to application of RF power at 200 MHz. In TST-2, ECH power is injected radially from the outboard side below the midplane. In start-up experiments by ECH power alone, the direction of I_p is determined by the direction of the vertical field, and is symmetric with respect to the vertical field. In this case, I_p is believed to be driven mainly by the pressure gradient. In the present experiment, the combline antenna excites a travelling wave in the toroidal direction. For wave injection in the co current drive direction, the plasma current is maintained stably after a rapid increase. In contrast, for wave injection in the counter current drive direction, the initial current rise saturates at a lower level, and a large amplitude modulation is seen on I_p thereafter. The line integrated electron density $n_e l$ has a modulation in phase with that on I_p. The power transmitted to the output port is modulated out of phase from $n_e l$ with a slight delay, indicating that the radiation resistance (indicative of wave excitation in the plasma) increases when the plasma density increases [13]. Since the line averaged electron density is of order 10^{17} m^{-3}, this result is consistent with COMSOL calculation of plasma loading

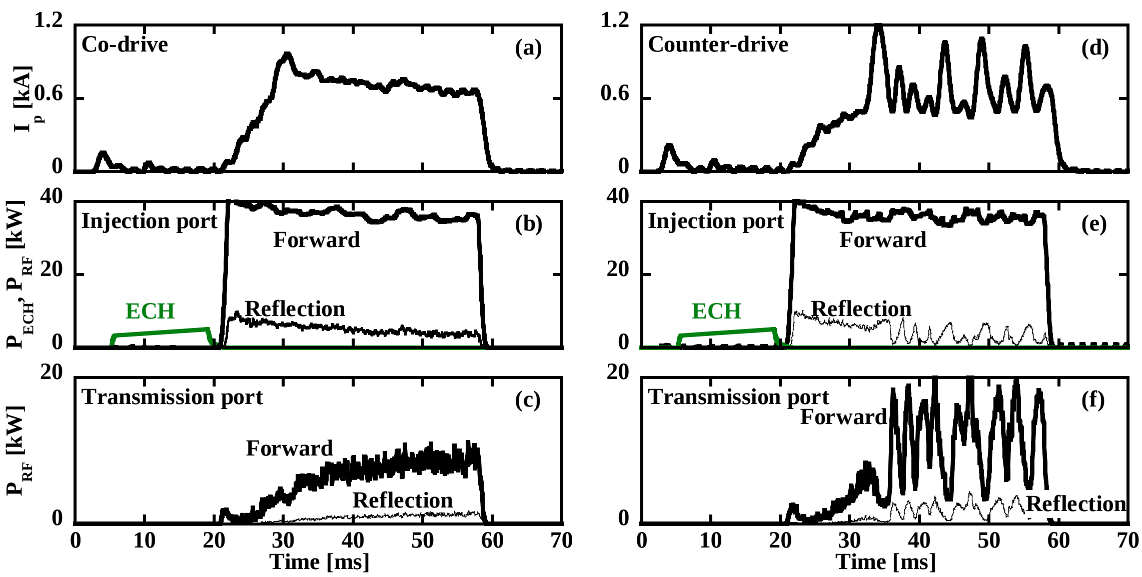

FIG. 9. Time evolutions of two discharges with co current drive (left columm) and counter current drive (right column). Plasma current I_p (a) and (d), EC power and RF forward and reflected powers at the input port of the combline antenna (b) and (e), and forward and reflected powers at the output port (c) and (f). Large amplitude modulation is seen on I_p for counter drive.

discussed in Sec. 2. The asymmetry observed for travelling wave excitation by the combline antenna suggests that direct current drive effect is playing an important role. Investigation of the physical mechanism of current drive will continue with higher RF power and improved antenna capable of exciting a travelling LHW directly.

5. Conclusions

The feasibility of I_p ramp-up by LHW in ST is investigated both theoretically and experimentally. In this study, TORLH full-wave calculations have shown that core current drive by LHW is possible in the low density, low I_p plasma formed by ECH. It is important to keep the density low during I_p ramp-up, and the wavenumber must be reduced as I_p increases to maintain core current drive. These calculations guide the optimization of the LHW antenna with correct polarization and wavenumber controllability. In TST-2, initial results were obtained using the combline antenna which can excite a travelling FW. Wave excitation was modeled by COMSOL, and FW excitation was confirmed. The decrease of the transmitted power to the output port with plasma density increase is consistent with the behavior predicted by COMSOL calculation. It was demonstrated that it is possible to form the ST configuration with $I_p \cong 1$ kA with RF power at 200 MHz. With co current drive a steady level of I_p could be sustained, while with counter current drive a large amplitude modulation of I_p was observed. The observed difference is attributed to RF driven current, rather than purely pressure gradient driven current. These initial results are encouraging, but since this scenario relies on mode conversion from the FW to the LHW, it is necessary to develop an antenna which can excite a travelling LHW directly. The TST-2 experiment can provide a scientific basis for the required capability of the CS for a compact low-aspect-ratio reactor.

Acknowledgments

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