Assessment of Current Drive Efficiency and Synergetic Effect for ECCD and LHCD in ITER Steady State and Hybrid Scenarios.

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Abstract. Steady state operation is preferable for fusion reactors. The possibility of extending the pulse length in ITER is considered taking into account the capabilities of the planned ECCD and LHCD. The ECCD efficiency for current drive at different locations is assessed. The possibility of extending the pulse length by the increase of the current drive efficiency due to the synergetic effect for combined ECCD and LHCD at the same location is assessed.

1. Plasma parameters and modeling description

Steady state (SS) and hybrid scenarios with Q > 5 are foreseen for ITER operation. In these scenarios the current flat top duration has to be increased to 3000 s and 1000 s respectively by full or partial replacement of the ohmic current by bootstrap, NB, EC and LH driven currents [1]. For ITER parameters and input power, such operation with Q > 5 will be possible with reduced plasma current I_p = 9 - 12 MA, providing the plasma energy confinement time τ_E will be better than that predicted by the H-mode scaling $\tau_{98y,2}$ [2]: $H_{H98y,2} = \tau_E/\tau_{98y,2} > 1$ [3]. Two types of SS scenarios have been assessed previously for ITER with plasma current I_p = 9 MA and simplified ECCD and LHCD modeling. A type-I SS scenario-4 was assessed to be possible in ITER with a moderate enhancement of plasma confinement $H_{H98y,2}$ = 1.3 and P_{NB} = 33 MW, P_{LH} = 37 MW used for noninductive current drive [4,5]. A type-II SS scenario-4 was shown to be a possibility with a high enhancement of plasma confinement $H_{H98y,2} \sim 1.7$, P_{NB} = 33 MW, P_{EC} = 20 MW [3].

In present studies, the calculations have been carried out for ECCD and LHCD corresponding to the ITER design. ECCD is considered for launch through the upper ports of EC waves at a frequency of f_{EC} = 170 GHz and a power of 20 MW. LHCD is considered for launch through equatorial ports with frequency f_{LH} = 5 GHz, and a power of 20 MW. Calculations are carried out for plasma parameters corresponding to ITER steady state scenarios [3, 4, 5].

The modelling is carried out on the basis of the OGRAY code originally designed for ECCD modeling [6]. The ECCD modelling includes the tracing of a Gaussian microwave beam and calculation of the corresponding quasilinear diffusion coefficients. The beam-tracing procedure is based on extended geometrical optics [7] and calculates the trajectory of the beam centre as well as the direction and values of elliptic Gaussian beam widths. The initial parameters for the beam tracing correspond to the ITER EC launching system. The absorption of the microwave beam is calculated from the Fokker-Planck equation. Thus, the quasilinear distortion of the distribution function is taken into account.

The beam-tracing calculation of LH waves is based on the Fast Ray-Tracing Code (FRTC) [8] combined with the ASTRA 1.5D transport code [9]. The LHCD is incorporated in the OGRAY in a simplified manner to estimate possible synergetic effects.

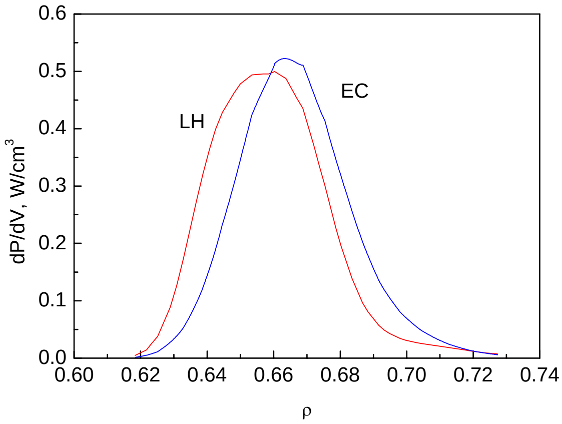


Fig. 1 Spatial alignment of the EC and LH power absorption for the ITER steady state scenario 4 (type-I) [5].

The ray-tracing LH modeling for ITER Scenario 4 shows that one-pass absorption takes place [10]. This enables a simplified calculation for LH power propagation in the OGRAY code. The ray tracing for propagation of LH waves is taken from FRTC code simulations [10], with a Gaussian power spectrum $P_{N||}$ approximating the power spectrum shape calculated by FRTC along the LH ray trajectories.

As a result of this simplification we obtained a narrower spatial LH power deposition profile than in [10], see Fig.1. This will cause some overestimation of the EC+LHCD synergetic effect.

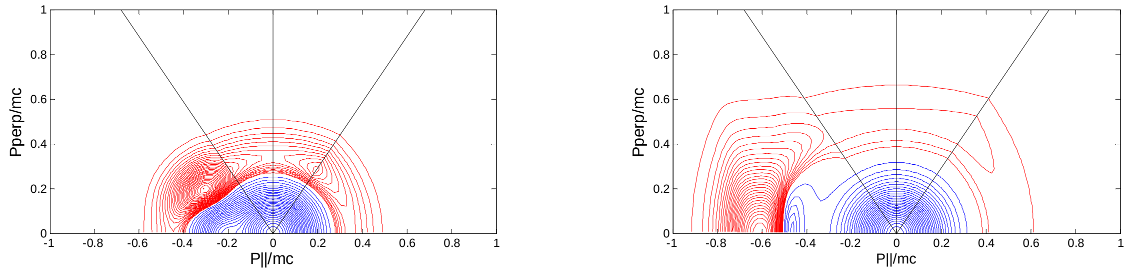
At the same time, the kinetic modeling was performed accurately. The OGRAY code has been modified to include both EC and LH quasilinear diffusion coefficients in the Fokker-Planck solver. The quasi-linear diffusion coefficient in the velocity space caused by LH waves absorption is taken according to [11]:

$$D_{LH} = 8\,\pi^2\, e^2\, N^2\, P_N(c/v_{||})\,(\omega V' r\, \partial D_0/\, \partial N_r v_{||}^3)^{-1},$$

where D_0 is a dispersion relation, V’ is volume radial derivative, P_N is a local power spectrum. Coulomb collisions are described by a linearized weakly relativistic collision term. The Fokker-Planck equation takes into account the existence of trapped electrons. The solution of the stationary Fokker-Planck equation determines the distribution function under the simultaneous action of EC and LH. In search of synergetic effects the current drive efficiency has been determined for EC and LH individually and for EC&LH acting together. The quasi-linear diffusion coefficients for LH and EC were calculated on the same magnetic surfaces and on the same grid in the momentum, $p_\perp = mv_\perp$, $p_{||} = mv_{||}$ space. The electron distribution function was determined by the solution of Fokker-Plank equation with simultaneous effects of LH and EC diffusion, as well as collisions. The absorption of LH and EC power along the trajectory of waves is calculated taking into account the quasi-linear distortion of the distribution function. The test runs of the code for either LH or EC showed that the driven current grows linearly with input power of the waves.

2. Assessment of the ECCD and combined ECCD/LHCD current drive efficiencies

The modeling has been done for ITER Scenario 4 [5], with frequencies corresponding to the ITER design f_{LH} = 5 GHz, f_{EC} = 170 GHz. The initial position of EC beam corresponded to the design of the upper launcher with remote steering. Calculations for estimation of the maximal synergetic effect correspond to the ITER design case R = 677.9 cm, Z = 428.5 cm with launching angles $\alpha = -\,59.73^o$, $\beta = 16.85\ ^o$.



a **b**

FIG. 2. Distortion of electron distribution function f(p⊥, $p_{||}$) from the Maxwellian f_M by EC(a) and LH (b) waves separately .The lines correspond to $f - f_M$ = const. $f - f_M > 0$ lines are shown in red, $f - f_M < 0$ lines are shown in blue. Straight lines correspond to the trapping area.

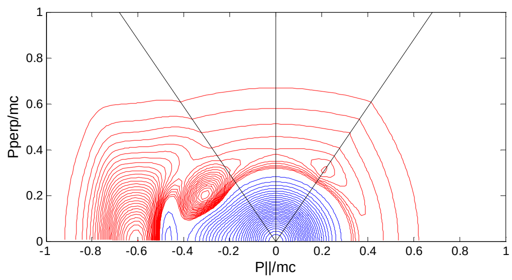


FIG. 3. Distortion of electron distribution function f(p⊥, $p_{||}$) from the Maxwellian f_M by ECand LH waves simultaneously.

The deviation of the electron distribution function from the Maxwellian $f - f_M$, is shown in figs. 2, 3. Under the action of the diffusion in the velocity space the particles are accelerated from the low momentum range (shown in blue) to the high momentum range (shown in red). The resulting asymmetry of distribution function generates the current. Comparing Fig.2 (a,b) one can see that the region enriched by electrons in the EC case ($N_{||} \approx 0.4$) is separated from the region affected by LH diffusion ($N_{||} \approx 0.5$). Thus, for the ITER LHCD and ECCD system parameters the alignment of the velocity space diffusion regions is not optimal for the synergetic effect.

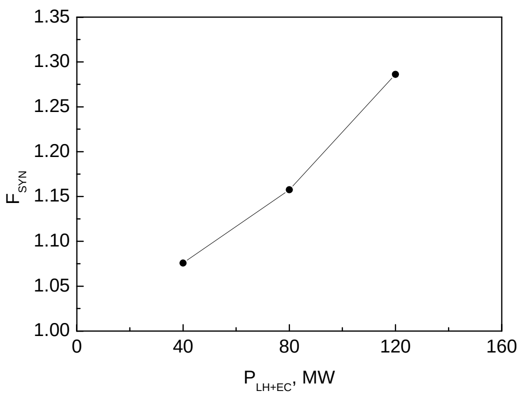


FIG. 4. Synergy factor $F_{syn} = (I_{LH+EC} - I_{LH})/I_{EC}$ as a function of input power ($P_{LH} = P_{EC}$).

Fig. 3 illustrates the simultaneous action of LH and EC. One can see that the general picture of the lines ($f - f_M$ = const) resembles the superposition of Fig.2 (a) and (b). The synergetic effect in this case is not prominent. Fig.4 shows the synergy factor $F_{syn} = (I_{LH+EC} - I_{LH})/I_{EC}$ as a function of input power ($P_{LH} = P_{EC}$). The synergetic effect grows with input power, but for ITER power levels $P_{LH} = P_{EC}$ = 20 MW it does not exceed 10% at maximum. Thus, in contrast with [12] for the ITER case the LHCD and ECCD can be considered as independent additive tools for control of the current profile in ITER.

Calculations of the distribution of plasma current carried out for the temperature and density profiles of the reference conditions [5] show that the synergetic effect from combined ECCD and LHCD does not provide an increase of current drive efficiency to the level sufficient for SS operation with Q > 5 and $H_{H98y,2}$ = 1.3.

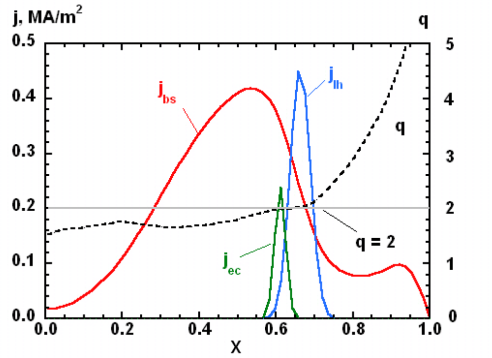


FIG. 5. Current densities and safety factor profiles for ITER reference scenario 4 [5].

Nevertheless, hybrid operation with Q > 5 will be possible with I_p = 9 MA, I_{EC+LH} > 1 MA provided by 20 MW of ECCD and 20 MW of LHCD, I_{NB} = 2.7 MA provided by the tangential NBI and I_{BS} = 4.0 MA of bootstrap current (Fig. 5). Additional I_{EC+LH} current reduces the loop voltage to 6 mV. This value is a factor of two smaller in comparison with the hybrid operation with NBCD only. Thus, the burn time of the hybrid operation will be limited only by the cooling capability (3000 s). Steady state operation will require further confinement improvement to $H_{H98y,2} \sim 1.5$.

It should be noted that in contrast with the reference scenario 4 [5], there is an area where the safety factor q drops below 2 but remains higher than 1.5. Thus, there will be no sawtooth oscillations and NTM stabilization can be required only at the q = 2 location, which can be provided by ECCD. Similar parameters (q > 1, q_{95} > 4, P_{loss}/P_{LH} > 2, $HH_{y,2} \sim$ 1.3-1.4, β_N > 2.5) are obtained in the improved H-mode operation [13]. Such a scenario fulfills the requirements of the ITER operational scenario-4 (t > 3000 s, Q > 5). Thus, it looks attractive for further consideration. Unfortunately, at present a “first-principle” model which describes scenarios of this type obtained in current experiments does not exist. Thus, the feasibility of such scenarios for ITER is not clarified yet.

3. Conclusions

The calculated synergetic effect of ECCD and LHCD on current drive efficiency is less than 10% for ITER parameters. Thus, ECCD and LHCD can be considered as independent tools for the ITER current profile control. Hybrid operation with Q > 5 and pulse length t > 3000 s will be possible with I_p = 9 MA, I_{EC+LH} > 1 MA provided by 20 MW of ECCD and 20 MW of LHCD, I_{NB} = 2.7 MA provided by the tangential NBI, and I_{BS} = 4.0 MA of bootstrap current. Similar parameters (q > 1, q_{95} > 4, P_{loss}/P_{LH} > 2, $HH_{y,2} \sim$ 1.3-1.4, β_N > 2.5) are obtained in the improved H-mode experiments [13]. Such a scenario fulfills the requirements of the ITER operational scenario 4 (t > 3000 s, Q > 5).

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