# Simulation of lower hybrid current drive in the presence of inductive electric field in the FT-2 tokamak

A. Saveliev, N. Teplova, G. Troshin, E. Gusakov, S. Lashkul, D. Kouprienko
and FT-2 team

*Ioffe Institute, Saint-Petersburg, Russia*

In this paper a new one-dimensional approach to the lower hybrid current drive (LHCD) modeling in the presence of inductive electric field is applied to calculate LHCD for deuterium plasmas at the FT-2 tokamak. The simulation results are compared to experimental data.

**Introduction.** Experimentally approved and validated methods of current generation in a tokamak are injection of neutral beams and using electromagnetic waves [1]. At present, the method of generating current by means of slowed-down high-frequency waves of the lower hybrid (LH) frequency range (Δf ≈ (1-10) GHz) is widely used in traditional type tokamaks (with an aspect ratio of R / a> 2) and has the highest theoretically and experimentally confirmed efficiency. The method is based on the effect of the transmission of a pulse by a slowed-down RF wave in the lower hybrid frequency range to electrons due to Landau damping. As a result, the electron distribution function (EDF) is deformed, which ensures an increase in the total current in the tokamak plasma. This method is still considered as a candidate for current generation in ITER [2, 3].

In most LHCD experiments the inductive electric field is present and can play a noticeable role in the LH current generation, especially during the transition to the stationary stage and in small tokamaks. Namely, the electric field enhances the accelerating wing and suppresses the deceleration wing of the EDF leading to an additional asymmetry of the EDF which may strongly change driven current profile and value. To calculate the EDF the 1D Fokker-Planck kinetic equation for the fast ($V_{||}/V_{T_e} \gg 1$) electrons is solved in the following form in standard notations:

$$\frac{\partial f}{\partial \tau} = E\frac{\partial f}{\partial v} + \frac{\partial}{\partial v}\left\{D(v)\frac{\partial f}{\partial v}\right\} + \beta\left(Z_{eff}\right)\frac{\partial}{\partial v}\left\{\frac{1}{v^3}\frac{\partial f}{\partial v} + \frac{f}{v^2}\right\} \quad (1)$$

Here $D(v)$ is the quasilinear diffusion coefficient that represents the effect of the waves, $v = V_{||}/V_{T_e}$, $V_{\mathrm{Te}} = \sqrt{T_e/m_e}$, $E = E_{||}/E_c$, $E_c = 4\pi e^3 n_e L/T_e$ , $L$ is the Coulomb logarithm and time is normalized to the Spitzer collision time $\tau = t/\tau_0$ , $\tau_0 = m_e^2 V_{T_e}^3/4\pi e^3 n_e L$. To reconcile the 1D solution with the prediction of the 2D theory we introduce a parameter $\beta =$

$(5 + Z_{eff})/5$, which actually means renormalization of the Spitzer collision frequency. The equation (1) includes the run-away problem leading to a divergence of the electron distribution function at wings where the electric field $E$ accelerates and decelerates electrons. For large machines where the RF pulse duration is longer than the time at which the steady-state distribution function of fast electrons is achieved the problem (1) can be treated as stationary providing a simple solution which has been obtained in [4]. The duration of the RF power pulse in the FT-2 tokamak is only $t_{RF}$=6ms which is almost equal to the time at which the steady-state distribution of fast electrons is reached. Under these conditions the stationary solution of (1) is not valid and the time evolution of EDF must be taken into account which is done numerically in the present paper.

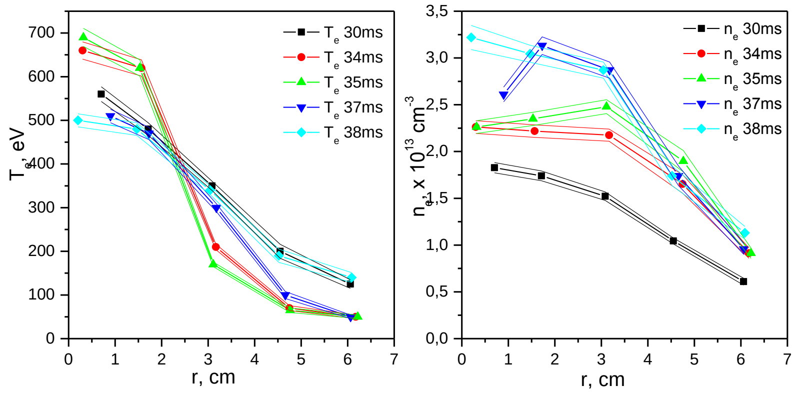
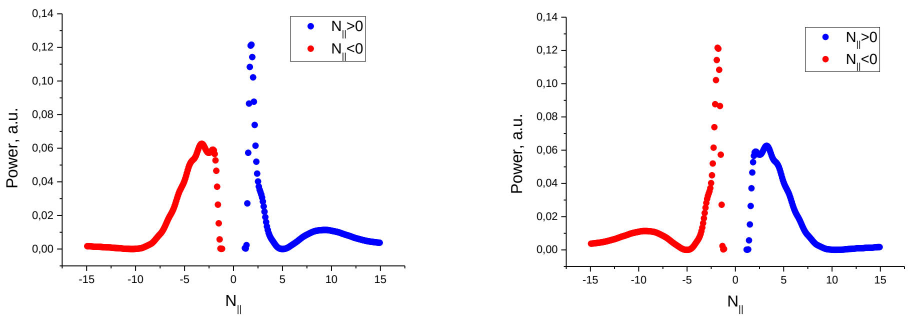


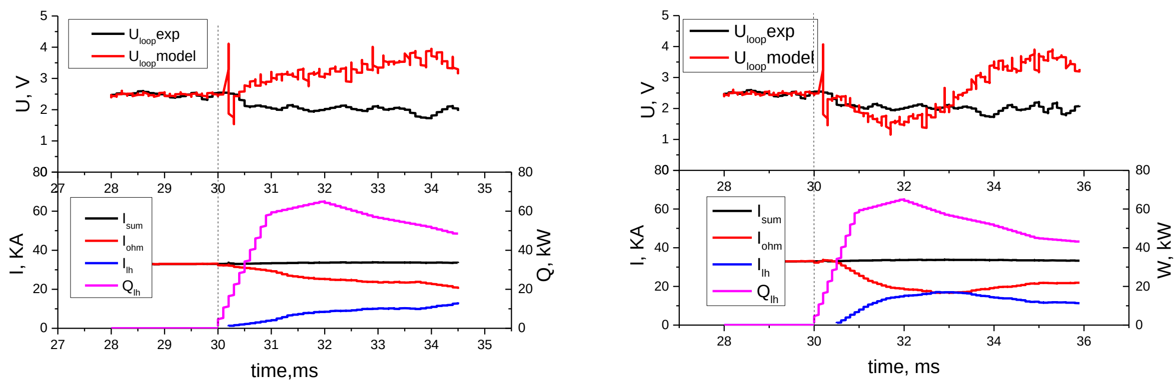

Figure 1. Electron temperature and density, discharge #140415, FT-2 tokamak

**Numerical analysis.** For numerical simulation we use the Fast Ray-Tracing Code (FRTC) [5], in which the ray-tracing calculations for describing wave propagation are combined with the time-dependent solution of the Fokker-Planck equation, incorporated into the ASTRA code [6]. We present results of single experiment modelling of the FT-2 tokamak (R=55cm, a=8cm) discharge #140415, RF power ~60kW, $t_{RF}$=6ms. In figure 1 the electron density (a) and electron temperature (b) for several time slices according to experimental data are shown. The $N_{||}$ spectra for the FT-2 tokamak LH two-waveguide antenna shown in figure 2 are calculated using the Grill3D code [7]. It is noticeable that positive and negative lobes of the spectra contain comparable amounts of the LH input power and therefore the spectra differ from the standard LHCD spectra. As it was shown in [4] the EDF time evolution must be taken into account for an adequate modeling of the FT-2 experiments. In the FT-2 LHCD experiments the phasing change from $+\frac{\pi}{2}$ to $-\frac{\pi}{2}$ does not change the sign of the loop voltage drop. This weak dependence of the loop voltage on the antenna phasing can be explained by the influence of the inductive electric field on the LH current generation. Aiming to perform numerical simulations close to the experiment we take into account the evolution of EDF, relatively weak electric field, equilibrium and of plasma parameters as calculated by ASTRA code and use a time-dependent solution of the Fokker-Planck equation. The whole scheme provides self-consistent simulation of plasma discharge, which can be compared to experimental results.




(a) (b)

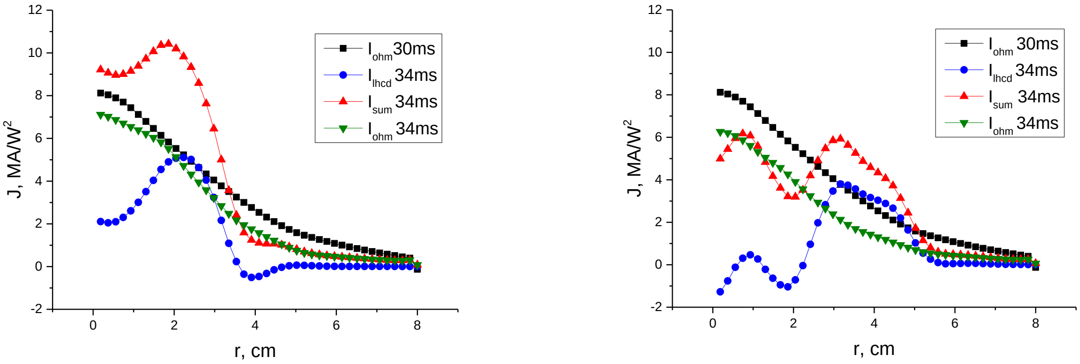
Figure 2. Calculated initial FT-2 $N_{||}$ spectra for $-\frac{\pi}{2}$ (a) and $+\frac{\pi}{2}$ (b) phasing of the FT-2 antenna




(a) (b)

Figure 3. The loop Voltage, experimental (black) and modeling (red); current LH(blue), ohmic (red) and total (black) and power (magenta) time dependencies for $-\frac{\pi}{2}$ (a) and $+\frac{\pi}{2}$ (b) phasing of the FT-2 antenna

In figure 3 we show the result of the loop voltage calculation which generally follows the experimental time trace, showing similarities for the phase $+\frac{\pi}{2}$. The agreement between modeling and experiment can be improved by introducing a small change to power sharing in the initial $N_{||}$ lobes or a small variation to the spectrum form because the spectrum is known only approximately. The disagreement can be also explained by growing $Z_{eff}$ during discharge from the value 1.4 at t=0.03s to 2.2 at t=0.036s linearly and by peaked shape of the temperature profile at t=0.034s and t=0.035s that results in the loop voltage growth. Figure 4 shows components of current density *J=dI/dS* radial profiles at time slice t=0.034s. Comparing to the previous results obtained by steady-state calculations [4, 8] the time-dependent approach presented in this paper is able to explain the significant current generation for $-\frac{\pi}{2}$ phase observed in FT-2 experiments. It is also important to note that for the both phases, $+\frac{\pi}{2}$ and $-\frac{\pi}{2}$ (co- and counter plasma current) of the antenna the direction of the current remains the same.




(a) (b)

Figure 4. Current density profiles ohmic (green), LH(blue), total (red at t=0.034s and ohmic(black) at t=0.03s for $-\frac{\pi}{2}$ (a) and $+\frac{\pi}{2}$ (b) phasing of the FT-2 antenna

**Conclusions.** The loop voltage variation and the LH current density have been calculated for the FT-2 tokamak using the FRTC, ASTRA and Grill3D codes. The comparison of the calculated loop voltage behavior and the experimental one has shown similarities for the phase $+\frac{\pi}{2}$. In spite of this, the fact that in the experiment there are no difference between the loop voltage drop sign obtained for phases $-\frac{\pi}{2}$ and $+\frac{\pi}{2}$ remains unclear. For further investigation of this phenomenon, special more detailed experiments are planned at FT-2 and Globus-M2 tokamaks allowing more accurate calculations.

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