Sample analysis of the influence of different parts of the spectrum on the lower hybrid current drive in the FT-2 tokamak

G. Troshin[1], E. Gusakov[1], N. Teplova[1], V. Khavin[2], S. Lashkul[1], D. Kouprienko[1] and FT-2 team

[1] *Ioffe Institute, Saint-Petersburg, Russia*

[2] *Saint-Petersburg Polytechnical University, Saint-Petersburg, Russia*

Introduction

Experimentally approved and validated methods of current drive 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.

Numerical model

For numerical simulation we use the Fast Ray-Tracing Code (FRTC) [2], 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 [3]. 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 most LHCD experiments the inductive electric field is present and can play a noticeable role in the LH current generation, especially in small tokamaks. Namely, the electric field enhances the accelerating wing and suppresses the deceleration wing of the electron distribution function (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 $v_{||}/v_{Te} \gg 1$ electrons is solved in the following form in standard notations:

$$\frac{\partial \mathrm{f}}{\partial \mathrm{t}} = \frac{\partial}{\partial \mathrm{v}}\left\{\mathrm{D(v)}\frac{\partial \mathrm{f}}{\partial \mathrm{v}}\right\} + \frac{\partial}{\partial \mathrm{v}}\left\{\frac{1}{\mathrm{v}^3}\frac{\partial \mathrm{f}}{\partial \mathrm{v}} + \frac{\mathrm{f}}{\mathrm{v}^2}\right\} \pm \mathrm{E}\frac{\partial \mathrm{f}}{\partial \mathrm{v}}$$

Here $D(v)$ is the quasilinear diffusion coefficient that represents the effect of the waves, $v = v_{||}/v_{Te}, v_{Te} = \sqrt{T_e/m_e}$, $E = E_{||}/E_c$, $E_c = 4\pi e^3 n_e L/T_e$, L is the Coulomb logarithm and time is normalized to the Spitzer collision time $\tau = t/\tau_0$, $\tau_0 = m_e^2 v_{Te}^2 / 4\pi e^3 n_e L$. To reconcile the 1D solution with the prediction of the 2D theory we introduce a parameter $\beta = (5 + Z_{\text{eff}})/5$, which actually means renormalization of the Spitzer collision frequency.

Aiming to perform numerical simulations in conditions close to the experiment we take into account the evolution of EDF, introduce relatively weak electric field, calculate the equilibrium and plasma parameters by ASTRA code and use a time-dependent solution of the Fokker-Planck equation. The whole scheme provides self-consistent simulation of plasma discharge.

Results of numerical modeling

We present results of a single experiment modelling of the FT-2 tokamak discharge #140415, RF power 60kW, duration of the RF power pulse t_{RF}=8ms [5]. In figure 1a the electron density (black) and electron temperature (red) for a single time slice according to experimental data are shown. The $N_{||}$ spectrum for the FT-2 tokamak LH two-waveguide antenna shown in figure 1b, is calculated using the Grill3D code [6].

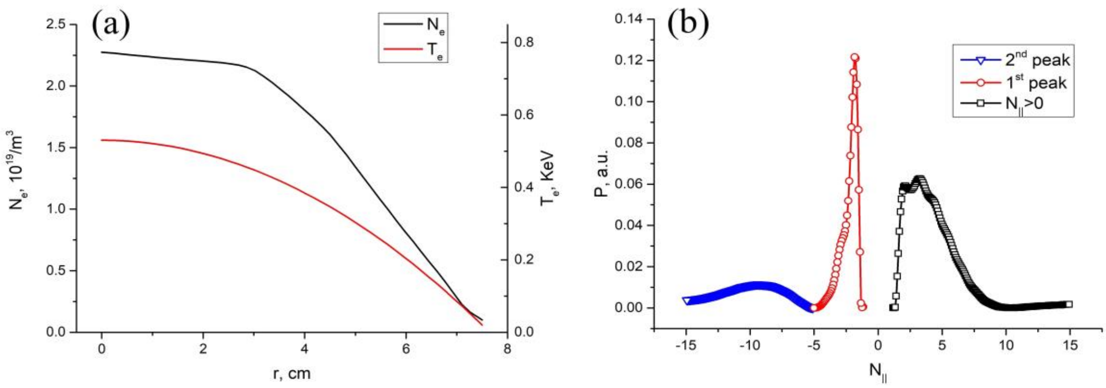

Figure 1. (a) The electron density (black) and the electron temperature (red) used for numerical modeling. (b) Calculated slowing down spectrum, 1st peak (red), 2nd peak (blue), positive $N_{||}$ (black)

To analyze the influence of different parts of the wave slowing down spectrum on the generation of LH driven current, a model calculation of the spectra of excited LH waves was carried out using the FRTC code incorporated into the ASTRA code. Spectrum calculations were performed for $\Delta\phi = +\pi/2$ value of phase shifts between the two waveguides of the antenna. The spectra of slowed-down high-frequency waves are characterized by bidirectionality (with respect to the plasma current) and the presence of several maxima in the distribution of high-frequency power $P(N_{||})$. For $\Delta\phi = +\pi/2$, the maxima correspond to the values of parallel refraction index $N_{||} = -9; -1.7$. Negative values correspond to the motion of the LH wave in the direction against the current, that is, in the direction of motion of the electrons producing the current. Subsequent modeling, taking into account the spectrum $P(N_{||})$ and experimental values of plasma parameters, made it possible to calculate the magnitude and the direction of the LH driven current, which is determined by the spectrum of excited LH waves. The decisive role of the synergetic effect associated with the interaction between different parts of the spectrum of the input LH wave was established. For a plasma at a central temperature Te(0) ~ 0.6 keV, effective generation of LH driven currents by a wave at $N_{||}$ = –1.8 is possible only in presence of a spectral region at $N_{||}$ = –9. Thus, for the experimental conditions at the FT-2 tokamak, a mechanism for overlapping the spectral gap is proposed, which is not associated with the parametric decay of the pump wave. The noted effect may be relevant for other facilities as well. In figure 2a the time evolution of LH driven current by negative parts of slowing down spectrum is shown.

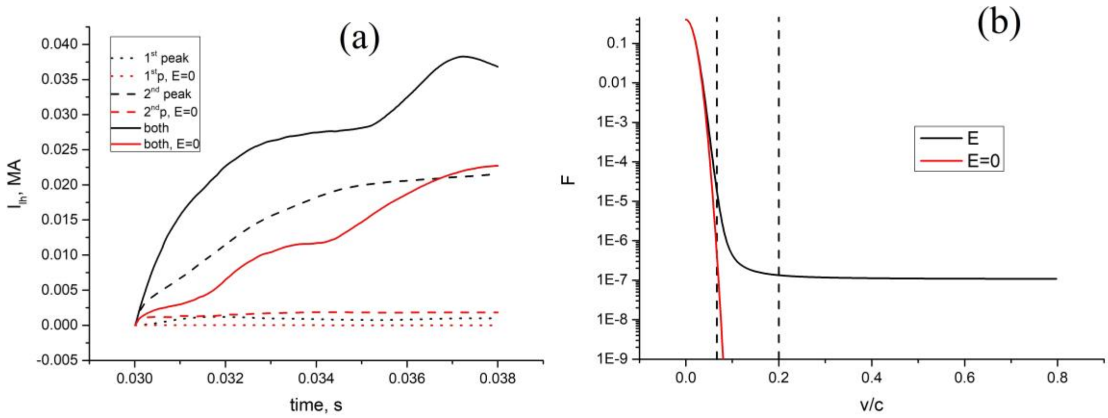

Figure 2. (a) LH driven current by 1st (dotted), 2nd (dashed) and full (solid) parts of spectrum in presence(black) and absence(red) of an inductive electric field
(b) The EDF in the presence(black) and absence(red) of an inductive electric field.

In case of zero electric field the 1st peak doesn't give substantial contribution to the result current, the 2nd peak alone generates ~2.5kA, whereas both of them generate ~23kA. The results obtained by using the peaks apart and together differ by more than a factor of 10. Waves at $N_{||}$~5-15 accelerate electrons and move them to high speed region in EDF to improve Landau damping for waves at $N_{||}$~1-5. In the presence of an inductive electric field the synergistic effect is less evident: the 1st peak generates ~2kA solely, the 2nd peak alone generates ~20kA, whereas both peaks generate ~35kA. These results differ by about a factor of 1.7. The improved generation for the 2nd peak can be explained by initial quasilinear plateau at the EDF, provided by inductive electric field. In figure 2b the comparison of electron distribution functions for both cases is shown. Dashed lines correspond to the 2nd peak's bounds $N_{||}$=5;15. The electric field accelerates electrons and increases number of them to interact with the waves which correspond to the 2nd peak. The difference between initial conditions for the two cases is shown by the area under the graph between dashed lines.

To characterize the absorption area in figure 3 the LH current drive density profiles in presence(a) and absence(b) of the electric field are shown.

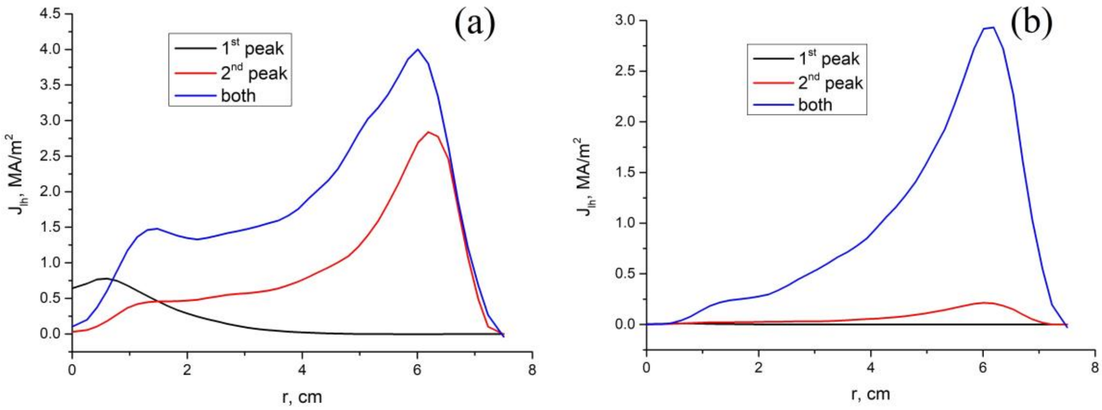

Figure 3. LH current drive density profiles in the presence(a) and absence(b) of inductive electric field

Black lines correspond to the 1st peak, red lines correspond to the – 2nd peak and blue lines correspond to the total spectrum. The described conditions for waves with $N_{||}$~5-15 are more favorable and therefore the generation of current drive occurs at periphery. The waves with $N_{||}$~1-5 form driven current as they penetrate deep into plasma, closer to the discharge axis.

Conclusion

A synergistic effect of different components of the LH wave slowing down spectrum on the lower hybrid current drive in a small modest parameters tokamak is shown to be very important. Its substantial effect on the total driven current as well as on the current density profile is demonstrated both in the prresence and absence of the inductive electric field.

Acknowledgements

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