Dynamic and stationary modeling of lower hybrid current drive in the FT-2 and the Globus-M2 tokamaks

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The development of non-inductive methods for current drive generation is a central problem in the development of a fusion reactor within the framework of the tokamak concept. The lower hybrid (LH) method can potentially be used to solve this problem, since it has one of the highest efficiencies of current drive (CD) generation [1]. Experimental study of the LH wave interaction with plasma is one of the main tasks of the FT-2 and Globus-M2 tokamak projects.

The FT-2 tokamak is a high aspect ratio machine with high magnetic field (R=0.55 m, a=0.08 m, $B_T \leq$ 3T, I_p=19÷40 kA). The LH waves are excited at frequency 920 MHz from the low field side in the FT-2 plasma by a two- waveguide antenna (grill) using various grill phasing [2]. The Globus-M2 is a spherical tokamak (ST) (R=0.36 m, a=0.24 m, $B_T \leq$ 1T, $I_p \leq$0.5 MA, vertical elongation k=1.6-2, LH operating frequency 2.45GHz). The well know problem of standard LHCD in STs where plasma central part is accessible only for waves with rather high parallel refractive indices due to comparatively low magnetic field can be solved by slowing down the initial spectrum of LH waves in the poloidal rather than the toroidal direction [3].

In the present paper we present results of stationary and time-dependent simulations of LHCD that combine transport (using ASTRA code [3]) and Fokker Planck simulations with a DC electric field and ray-tracing (using the Fast Ray Tracing Code (FRTC) [4,5]) analyses. The modeling is applied to the experiments at the FT-2 and Globus-M2 tokamaks. The Grill3D code [6] was used to calculate the spectrum of the longitudinal refractive index of a lower hybrid wave launched into the plasma by two-waveguide antennae.

For small tokamaks as Globus-M2 and FT-2 the LH pulse duration is comparable or smaller than the time, at which the steady-state distribution function of fast electrons is reached. That makes the non-stationary LHCD simulation accounting for the transit phenomena mandatory task for these tokamaks. Therefore, the original FRTC code was modified, its dynamic version was created, in which the quasilinear diffusion coefficient calculated from the absorbed power, is averaged over the surface of a constant magnetic flux and is used to iteratively solve the Fokker-Planck equation. A block diagram of the integration of the FRTC code into the ASTRA code is shown in the figure 1.

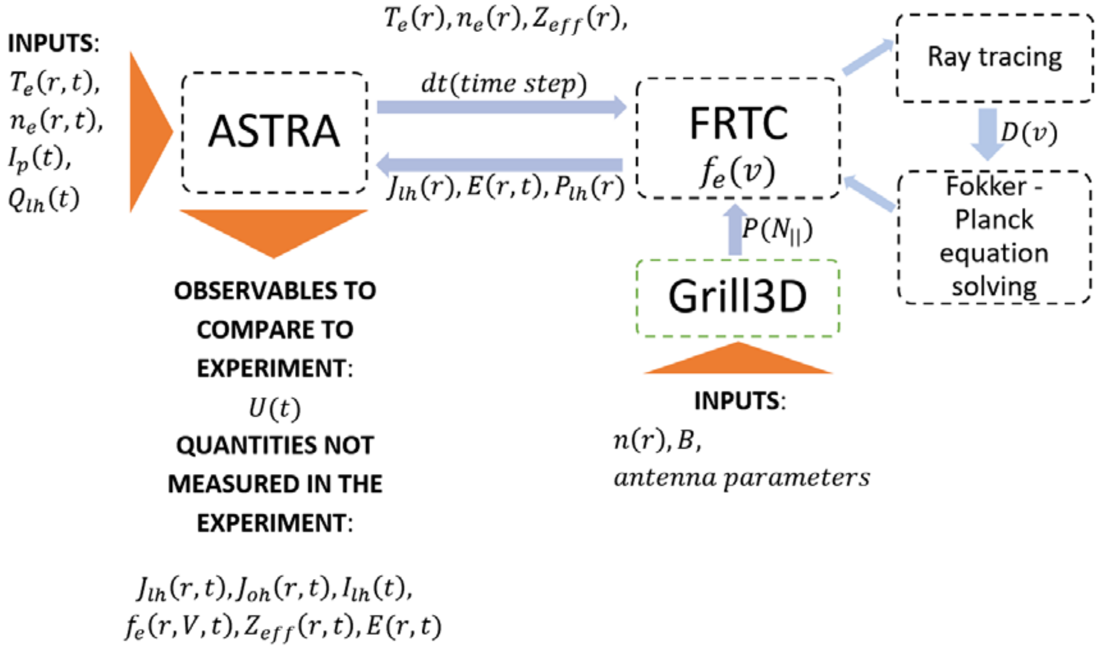

Figure 1. FRTC integration in ASTRA code using Grill3D.

The ray trajectories are calculated in the cold plasma approximation, since this approximation quite adequately describes the propagation of LH waves at frequencies above the lower hybrid frequency. We describe the ray-tracing procedure which solves numerically the following system of canonical equations, describing the propagation of a separate spectral component of the launched spectrum $\frac{d\vec{r}}{ds} = -\frac{\partial H/\partial \vec{k}}{|\partial H/\partial \vec{k}|}, \frac{d\vec{k}}{ds} = -\frac{\partial H/\partial \vec{r}}{|\partial H/\partial \vec{k}|}$, where s is the coordinate along the ray, $\vec{r}$ and $\vec{k}$ - generalized coordinates: spherical coordinates and wave vector. For standard tokamaks with a large aspect ratio, the Hamiltonian $H_0 = \varepsilon N_\perp^4 + \left[(\varepsilon+\eta)(N_\parallel^2 - \varepsilon) + g^2\right]N_\perp^2 + \eta\left[(N_\parallel^2 - \varepsilon)^2 - g^2\right]$, where ε, η and g are the components of the dielectric tensor, adequately describes the propagation and absorption of waves in LH experiments, however, such a classical approach is not applicable for spherical tokamaks, because, its predictions on transparency differ from those of the full-wave calculation [8]. In this case, a modified dispersion equation should be used $H = H_0 + H_1$ that takes into account the gradient corrections [3]: $H_1 = G'(\eta - N^2)(\varepsilon - N^2)/N^2$, where the gradient term is $G' = \nabla g \cdot (\vec{N} \times \vec{e}_\parallel) - g\vec{N} \cdot \nabla \times \vec{e}_\parallel$, where $\vec{e}_\parallel = \vec{e}_z = \vec{B}/|\vec{B}|$ is the unit vector along the magnetic field.

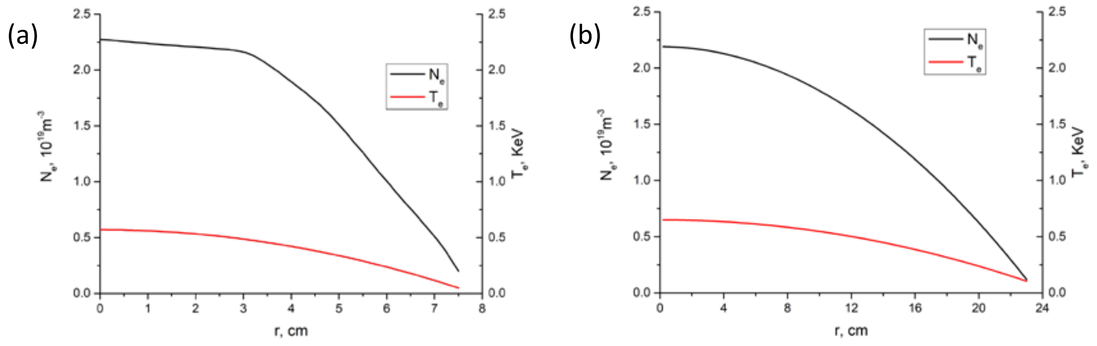

Figure 2. Plasma density (black) and temperature (red) profiles for (a) the FT-2 and (b) the Globus-M2 tokamaks.

In figure 2 we show the plasma density and temperature profiles used for stationary and time-dependent simulations of LHCD. In figure 2a the profiles correspond to a single LH discharge #140415 at the FT-2 tokamak, RF power 60kW, duration of the RF power pulse t_{RF}=8ms, plasma current 32kA [2]. In figure 2b we show the plasma density and temperature profile model as usually obtained from discharges at the Globus-M2 tokamak, RF power 120kW, duration of the RF power pulse t_{RF}=8ms, plasma current 185kA .

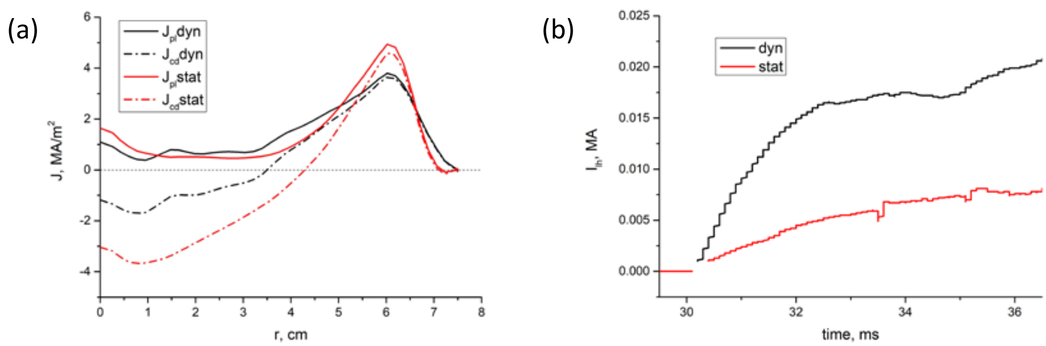

Figure 3. Dynamic and stationary modeling for the FT-2 tokamak. (a) current drive (solid) and plasma current (dashed) density profiles at time slice 36ms, (b) time evolution of the plasma current for dynamic (black) and stationary (red) calculations

In figure 3 we compare the dynamic and stationary modeling for the FT-2 tokamak. In figure 3a we show the current density profiles calculates at time slice 36ms close to the steady-state regime. The LH current is driven at the periphery for the both cases. As it is shown in figure 3b the stationary version of the FRTC code underestimates the value and the growth rate of the LH current obtained in the FT-2 compared to the dynamic code. The result of the dynamic code matches the results obtained in the FT-2 experiments by estimating the loop voltage drop of the value of 50-70%[2].

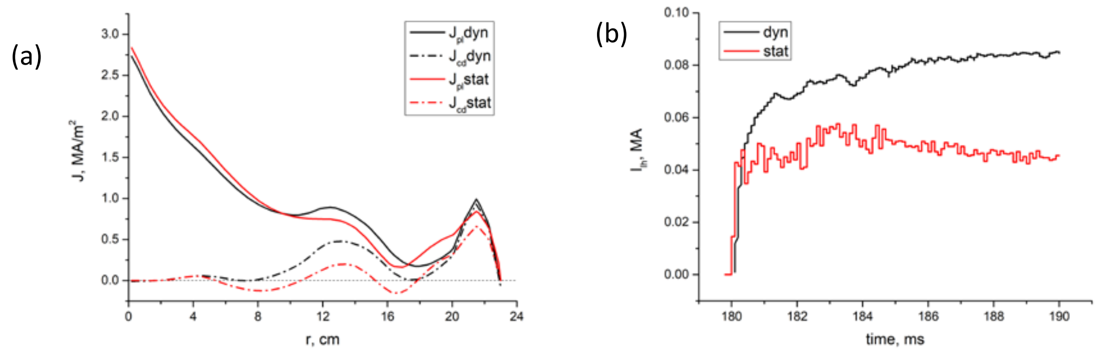

Figure 4. Dynamic and stationary modeling for the Globus-M2 tokamak. (a) current drive (solid) and plasma current (dashed) density profiles at time slice 190ms, (b) time evolution of the plasma current for dynamic (black) and stationary (red) calculations

In figure 4 we compare the dynamic and stationary modeling for the Globus-M2 tokamak. In figure 4a we show the current density profiles calculates at time slice 190ms close to the steady-state regime. The LH current is driven at the center for the both cases. In figure 4b the time evolution of the LH current shows that the LH current calculated using stationary version of the FRTC code is underestimated comparing to the value of the LH current obtained in the Globus-M2 experiments by estimating the loop voltage drop of the value of 30-70%[9].

Conclusion

In the present paper we have shown the results of stationary and time-dependent simulations of LHCD for the FT-2 and the Globus-M2 tokamaks. Calculation for the ST tokamak requires taking into account the gradient terms. The time-dependent electron kinetic calculations are shown to be important for small tokamaks.

Acknowledgements

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