BASIC TOROIDAL EFFECTS ON ALFVÈN WAVE CURRENT DRIVE IN LOW ASPECT RATIO TOKAMAKS

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Alfvèn Wave Current Drive (AWCD) in low aspect ratio (START-like, [1]) tokamak ($R/a \approx 1.4$) is calculated in this work using (i) the best fitted functions describing the START equilibrium state with neo-classical effects [2], (ii) 2D full-wave equation solutions obtained by a powerful finite element code [3] and (iii) the current drive expressions derived in [4].

General Consideration

A time-averaged rf current drive parallel to the equilibrium magnetic field, $\boldsymbol{B}_0$, can be defined as

$$j_{e\|} = \sigma_{\|} \, \frac{F_{e\|}}{N_{e0} q_e} \, , \qquad (1)$$

where $F_{e\|}$ is the time-averaged ponderomotive force exerted on electrons, N_{e0} — the equilibrium electron particle density and $\sigma_{\|}$ — the plasma parallel conductivity.

We consider three contributions to $F_{e\|}$ given by [4] ($\mathbf{F}_e = \mathbf{F}_{ne} + \mathbf{F}_{de} + \mathbf{F}_{pe}$):

$$\mathbf{F}_{ne\|} = -e \, (\, N_{e\omega} \mathbf{E}_\omega \,)_0 \, , \quad \mathbf{F}_{de\|} = (\, \mathbf{j}_{e\omega} \times \mathbf{B}_\omega \,)_0 \, , \quad \mathbf{F}_{pe\|} = -\nabla_i \left(\frac{j^i_{e\omega} \mathbf{j}_{e\omega}}{\varepsilon_0 \omega^2_{pe}} \right)_0 \, ; \qquad (2)$$

here, "0" denotes the time-average of the oscillating (rf) values (subscript $_\omega$). In eq.(2), $\mathbf{F}_{ne}$, $\mathbf{F}_{de}$ and $\mathbf{F}_{pe}$ represent, respectively, the Lorentz, the Hall (dynamo) and the wave pressure gradient connected forces.

Lorentz Force

Linearizing continuity equation and using the definition $\boldsymbol{j}_{e\omega} = -N_{e0} \boldsymbol{v}_{e\omega}$, one obtains:

$$F_{ne\|} = \frac{i}{4\omega} \left[E_{\|} \, (\nabla \cdot \boldsymbol{j}^*_e) - c.c. \right] \, , \qquad (3)$$

where $E_{\|} = \boldsymbol{E} \cdot \boldsymbol{B}_0 / B_0$ and $\boldsymbol{E}$ is the amplitude of $\boldsymbol{E}_\omega = \boldsymbol{E} \exp(-i\omega t) + \boldsymbol{E}^* \exp(+i\omega t)$.

Hall Term

By Faraday's law, from eq.(2) one obtains:

$$F_{de\parallel} = -\frac{i}{4\omega B_0} \{\boldsymbol{B}_0 \cdot [\boldsymbol{j}_e^* \times (\nabla \times \boldsymbol{E} - c.c.]\} \ . \tag{4}$$

Pressure Gradient Term

In covariant form, one has:

$$F_{pe\parallel} = -\frac{i}{4\omega B_0} \left[\boldsymbol{B}_0 \cdot \nabla_i \left(\frac{i\omega}{\varepsilon_0 \omega_{pe}^2} j_e^i \boldsymbol{j}_e^*\right) - c.c.\right] \ , \tag{5}$$

where $\omega_{pe}^2 \equiv N_{e0} e^2 / \varepsilon_0 m_e$.

Tokamak Case

In order to apply the eqs.(3)–(5) to a tokamak case, we consider the quasi-toroidal coordinates (ρ, θ, ϕ) defined by the relations $R = R_0 + \rho \cos\theta,\ Z = \rho \sin\theta,\ \phi = -\phi'$.

Numerical Results and Conclusions

Illustrative results for the Alfven wave current drive in a spherical START-like tokamak, based on the algorithm described above, are presented in Figs.1–2 (the normalization factor j_0 is the maximum equilibrium current density in START [2]). Our results clearly demonstrate the conversion phenomenon and generation of a significant component of non-inductive AWCD; for the parameters used ($m = 3,\ n = 1,\ \omega = 1.5 \cdot 10^7\, s^{-1}$), the dynamo (helicity injection) contribution is by far dominant. The conversion of fast (antenna-launched) wave to the short-wavelength Alfvèn wave takes place in a narrow region ($\theta \approx \pi$) and is localized at $\rho \approx a/2$. The current drive and power deposition in this region (see the equatorial profiles in Fig.2) are significant. The narrowness (in θ) of the conversion layer can result from the strong toroidicity effect on the θ-dependence of $k_\parallel$. The effect of the pressure gradient term is not illustrated here as being negligibly small compared with the Lorentz and the Hall ones.

An optimization of this AWCD requires a proper selection of the wave (antenna) parameters for the specific tokamak under consideration.

References

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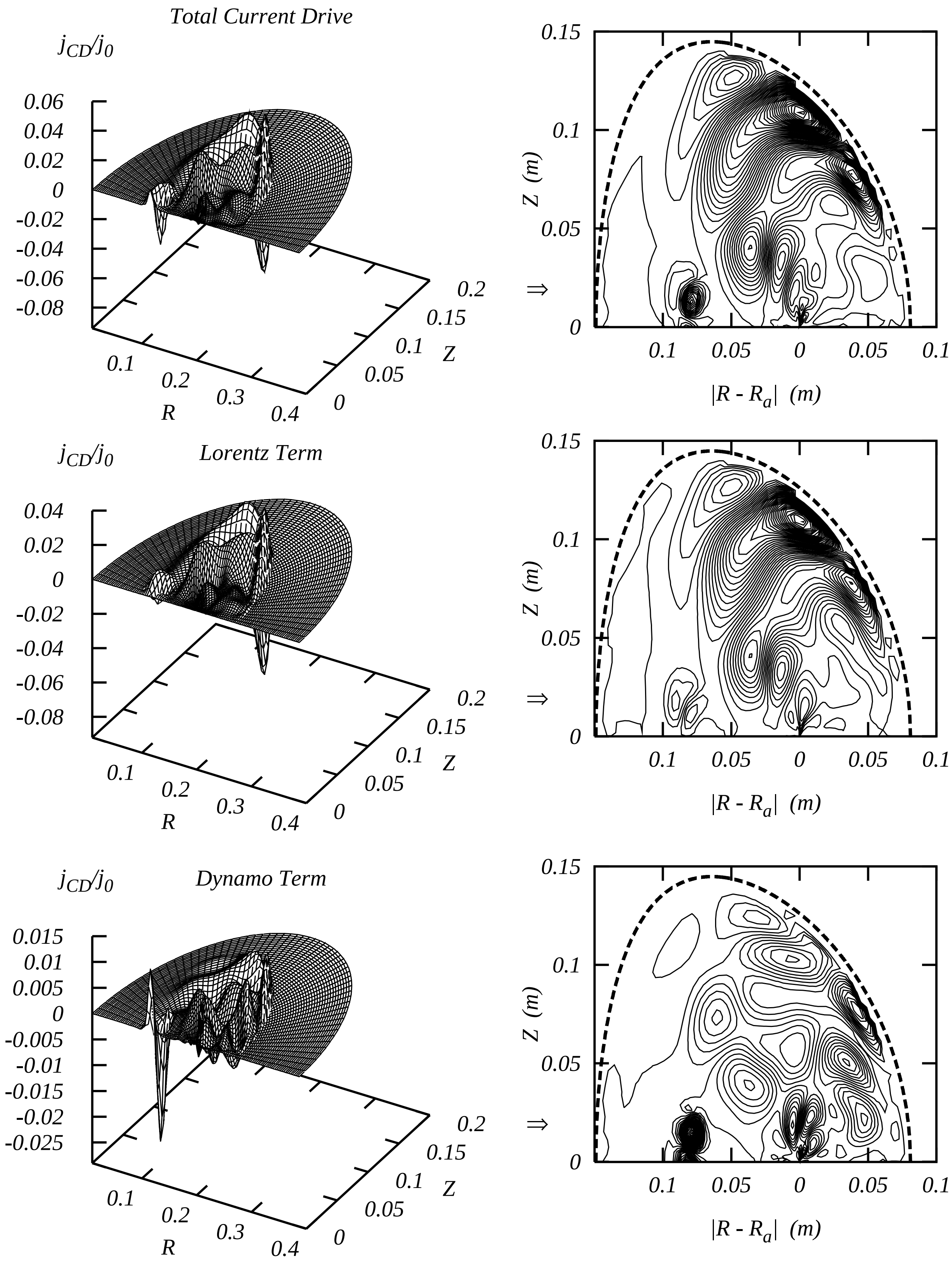

Fig. 1. Computed AWCD. Left (top → bottom): (R,Z)-dependence of total CD, Lorentz and Dynamo Terms. Right: corresponding iso-contours.

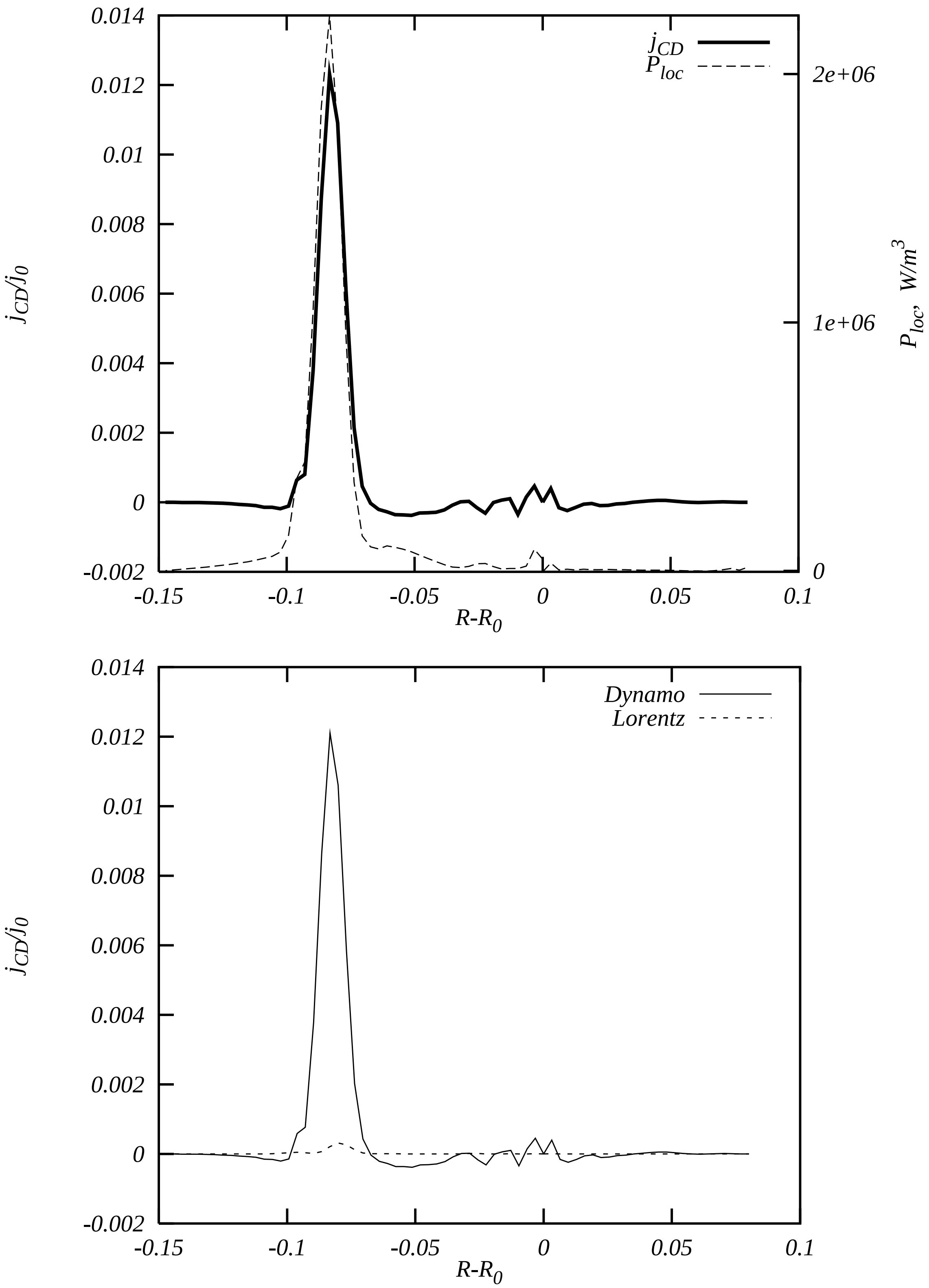

Fig. 2. Top: equatorial profiles of total AWCD (solid) and local power deposition (dashed). Bottom: equatorial profiles of the Dynamo (solid) and Lorentz (dashed) terms.