

## Self-consistent modelling of FWCD in tokamak plasmas

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### Abstract

We present here simulations of Fast Wave Current Drive (FWCD) scenarios applied to the ITER tokamak. To this aim, the full wave code EVE[1] has been supplemented by a kinetic module to evaluate the current drive efficiency. The obtained values are compared to semi-empirical formulae often used to describe radiofrequency (RF) current drive in ongoing and future experiments.

The operation of tokamaks relies on the drive and sustainment of a significant fraction of the toroidal current by non-inductive methods[2]. Several schemes involving RF waves in the Ion Cyclotron Range of Frequencies (ICRF) have been proposed and are being evaluated in ongoing fusion experiments. Among these methods, FWCD is obtained by launching waves with toroidally asymmetric spectra and appropriately tuning the generator frequency to maximise the amount of driven current per unit of injected RF power[3]. Owing to the absence of stringent accessibility limitations for the fast magnetosonic wave, and to the availability of reliable RF generators in the ICRF, this method is particularly attractive for next-step fusion reactors[4]. On the other hand, this scheme is known to be experimentally challenging[5] and therefore, the actual feasibility of FWCD in ITER still requires thorough evaluation. Among the various modelling efforts which have been pursued[6, 7, 8], the approach followed in Ref. [9] has the advantage of treating the wave and kinetic problems in a self-consistent fashion. Due to numerical limitations, however, a perturbation method was used to evaluate the parallel electric field  $E_{\parallel}$ . In this work, the same approach has been followed, but the multi-dimensional full wave code EVE[1] directly handles  $E_{\parallel}$ . EVE has also been supplemented by a module computing the quasilinear (QL) diffusion coefficient describing the interaction between the fast wave and the thermal electrons. In the framework of the variational theory used in EVE, which is based on canonical action-angle coordinates  $(J_i, \Phi_i)$ , the diffusion coefficient has the simple form

$$D_{ij}^{(QL)} = \pi \sum_{0, N_2, N_3=N} N_i N_j |\delta h_{0, N_2, N}|^2 \delta(\omega - N_i \Omega_i), \quad (1)$$

with  $\Omega_i \equiv \partial H / \partial J_i$ ,  $H$  being the unperturbed particle Hamiltonian.  $\omega$  is the wave frequency,  $N$  is the toroidal number and the sum is performed over all possible values of  $N_2$ . The advantage of the approach followed here is that the expressions used to evaluate the individual contributions

$\delta h_{0,N_2,N}$  to the QL diffusion operator are the same expressions as the ones used in EVE, making the wave and kinetic calculation naturally self-consistent. It should be noted that although the obtained operator acts on the action variables, it is readily transformed into an operator acting on the more convenient adiabatic invariants[10].

As mentioned in Ref. [7], both the wave code and the associated kinetic module can be used to evaluate the power absorbed by electrons. The obtained results have to be in agreement for the validity of the calculation to be asserted. Fig. 1(a) shows that this is indeed the case. It should be pointed out that the evaluation of  $D_{ij}^{(QL)}$  has been found to be demanding in terms of computational requirements and it is therefore sensible to perform comparisons with faster methods such as the Ehst-Karney (EK) parametrisation, which is widely used to estimate the current drive efficiency accounting for trapped effects[11]. Fig. 1(b) shows that for the considered parameters, the predicted current is in good agreement between both method.

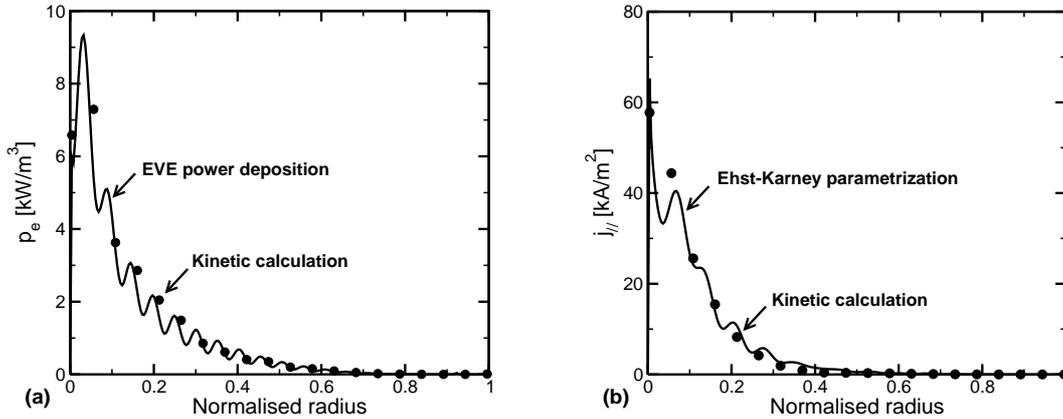


Figure 1: (a) Power absorbed by electrons computed by EVE (solid line) and by the kinetic module (full circles). (b) Driven current deduced from the EK parametrisation (solid line), and from the kinetic calculation (full circles). The result is given for 1MW of total absorbed ICRF power, and corresponds to the DT(He-3) scenario at  $f = 53\text{MHz}$ .

In order to investigate the relevance of FWCD for ITER[12], the parameters listed in Ref. [13] have been used as a reference:  $R_0 = 6.21\text{m}$ ,  $a_0 = 1.96\text{m}$ ,  $n_{e0} = 6 \times 10^{19}\text{m}^{-3}$ ,  $T_e(0) = T_i(0) = 17\text{keV}$  where “i” designates the plasma thermal ions: tritium (T), deuterium (D), helium-3 (He-3), thermalised helium-4 (He-4) and beryllium (Be). Also considered are fusion alphas ( $\alpha$ ), modelled by an equivalent Maxwellian with  $T_\alpha(0) = 600\text{keV}$ . Two situations are compared: second harmonic tritium heating (T-2) with concentrations  $\eta_T = \eta_D = 42\%$ ,  $\eta_{He-4} = 5\%$ ,  $\eta_\alpha = \eta_{Be} = 1\%$ ; and helium-3 minority heating (DT(He-3)) with  $\eta_T = \eta_D = 38\%$ ,  $\eta_{He-3} = 4\%$ ,  $\eta_{He-4} = 5\%$ ,  $\eta_\alpha = \eta_{Be} = 1\%$ . The ICRF antenna is assumed to be operated in dipole phasing, characterised by a toroidal modenummer  $N = 33$  and the frequency is varied between 35MHz

and 55MHz. EVE has been run to estimate the power deposition for both scenarios. The result is shown on Figs. 2(a) and (b).

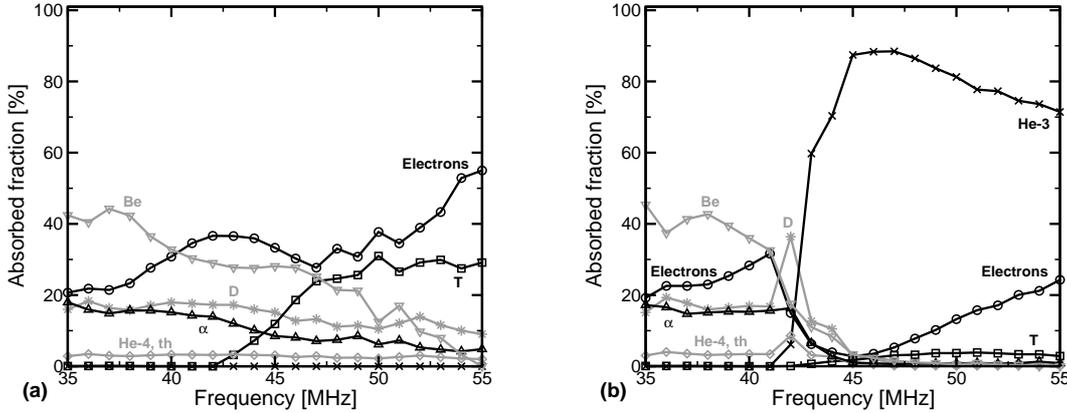


Figure 2: Comparison of the power split calculated by EVE (a) in the second harmonic tritium heating scenario; (b) in the helium-3 minority heating scenario.

In the two cases, the absorption by beryllium ions and alphas is far from negligible, especially at low frequency. The T-2 scenario results in a rough equipartition of the absorbed power between electrons and ions. On the other hand, the DT(He-3) scenario clearly favours ion heating for  $f \gtrsim 45$  MHz. It should be noted that the per-pass damping rate is also found to be improved, and the presence of helium-3 ions is expected to be beneficial in terms of discharge performance[14]. The drawback of the latter scenario, as far as FWCD is concerned, is that the electron damping is largely reduced.

In order to estimate the amount of driven current in each situation, the EK parametrisation is employed with the power deposition calculated by EVE. In all cases, the power damping by electrons is found to be centrally peaked (see, e.g., Fig. 1(a)). The obtained current density is subsequently integrated to estimate the FW current. The efficiency  $\eta_{FWCD}$  is defined as the ratio between this current and the total absorbed ICRF power. Another useful figure is the normalised efficiency  $\tilde{\eta}_{FWCD} \equiv \eta_{FWCD} R_0 \bar{n}_e$  where  $\bar{n}_e$  is the line-averaged electron density. The obtained result is shown on Figs. 3(a) and (b).

As expected, the highest FWCD efficiency is obtained in the absence of helium-3 and globally increases with the wave frequency up to roughly  $0.15 \times 10^{20} \text{ A/W/m}^2$ . In the DT(He-3) scenario, the higher ion absorption causes the current drive efficiency to be significantly reduced, reaching  $0.08 \times 10^{20} \text{ A/W/m}^2$ . It may be noted that the obtained results are in good agreement with those given in Ref. [13] and indicate that a total current of about 20kA can be driven per megawatt of absorbed ICRF power. This value should be considered as an estimate of the maximum driven current. More precise assessments require to consider the effects of an-

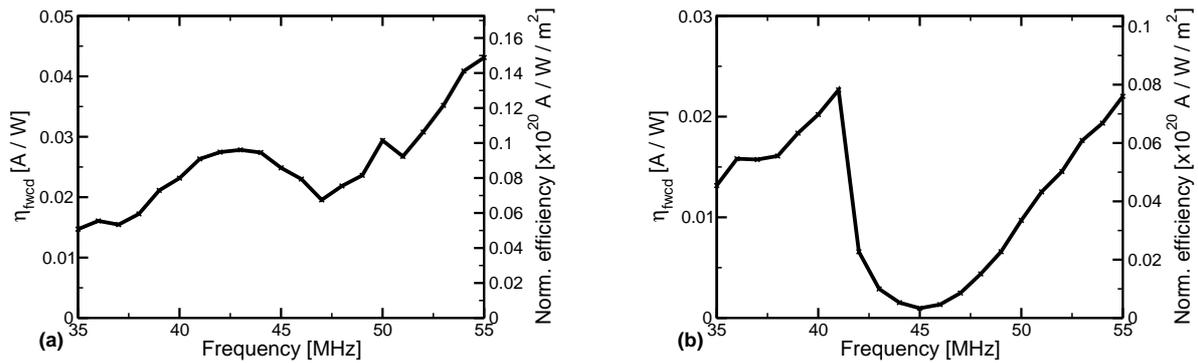


Figure 3: FWCD efficiency in ITER versus frequency in (a) the T-2 scenario, (b) the DT(He-3) scenario. The efficiency is given in A/W (left y-axis), or in units of  $10^{20}$  A/W/m<sup>2</sup> (right y-axis).

tenna toroidal spectrum, ion tails and associated orbits. Even if the obtained FWCD efficiency is not sufficient to make it viable for the bulk of non-inductive current drive in ITER, its central location and the flexibility provided by the antenna phasing make it a useful tool to drive a moderate amount of current near the magnetic axis, which may be desirable in terms of discharge stability for future devices[15].

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