Simulations of fast-wave current drive in pulsed and steady-state DEMO designs

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Abstract. Electromagnetic waves in the ion-cyclotron (IC) range of frequencies are presently investigated as possible current drive (CD) systems in fusion reactors. Among many physical and technical issues, an accurate description of radio-frequency (RF) power absorption by fusion-born alpha particles is of special importance, since RF heating of these particles is not only detrimental for the CD efficiency, but might worsen the operative conditions by increasing their prompt losses.

The capability of the full-wave TORIC code has been recently augmented to account for RF absorption by fusion-born alpha particles, calculated to all-orders in finite Larmor radius and with a realistic distribution function. Here, we present simulation with TORIC addressing the sensitivity of current drive efficiency on the design of a future reactor, in particular density and temperature profiles, magnetic field intensity, and plasma dimensions. For this purpose, we have investigated possible frequency windows for CD for two proposed versions of the DEMO reactor, namely its pulsed and its more ambitious steady-state design. The important role of the antenna for a realistic estimate of the CD efficiency is pointed out.

1. Introduction

The European Power Plant Physics and Technology (PPPT) task-force, established to identify the main physics and technological challenges for a fusion reactor [1], has recently focused its analysis on two designs of the demonstration reactor DEMO [2]. The “Early DEMO” (DEMO1), based on a “conservative extrapolation” of present knowledge and available technology, is meant to be a short- to medium-term target. As a consequence, DEMO1 is pulsed, with a duty cycle of about 2 hours, less than what is expected in a commercial reactor (about 8 hours). The “advanced DEMO” (DEMO2), by contrast, ambitiously aims to be compact and to operate in steady-state, two features which are economically appealing.

Both approaches require external systems for current drive (CD): in DEMO1 CD is foreseen to extend the pulse length to reduce the material fatigue and to increase the power-plant efficiency, whereas in DEMO2 CD should complement the bootstrap current during the recovery of the flux in the central solenoid. The CD systems used in past and present devices are based either on propagation and absorption of radio-frequency (RF) waves in the lower-hybrid (LH), electron-cyclotron (EC), and ion-cyclotron (IC) ranges of frequencies, or on the injection of energetic neutrals which ionize in the plasma (neutral-beam injection (NBI)) [3, 4]. Numerical simulations have been recently done to quantitatively address the capabilities of an ICRF system in driving current in DEMO [5, 6, 7]. A key issue in optimizing ICRF-CD is to enhance as much as possible the fraction of RF power directly deposited in the electrons by reducing competition.
by ion absorption. In particular, in an ignited plasma the fraction of RF power absorbed by fusion-born alpha particles can be substantial, and detrimental for the operation of the reactor by increasing their prompt losses and thus the wall thermal loading. Since this fraction depends sensitively on the distribution function of these alpha particles, it is important to model it accurately in the simulations, namely when evaluating the coefficients of the wave equation. In the full-wave TORIC code [8] the slowing-down distribution function [9] has been recently implemented for this purpose [16]. It has been shown that approximating it with an equivalent Maxwellian having the same density and energy content as the true distribution appreciably overestimate the RF power absorbed by energetic particles [16].

2. Constraints on fast wave current drive in ignited plasmas

In contrast with other CD schemes, CD by the fast wave (FW) in the IC range of frequencies in reactor plasmas does not require major technical developments for the sources. The most difficult element for a successful FWCD system design is, however, the launching structure. Even disregarding for the present all technical aspects, the physics of FWCD poses contradictory demands on the geometry of the antenna, obliging to compromises in its design. The sensitivity of the CD efficiency on the plasma parameters, moreover, will require a degree of flexibility not easily realizable.

As well-known, the CD efficiency depends in the first place on the ratio of the parallel phase velocity to the electron thermal speed \( \frac{x_e}{k} v_{\text{the}} \) with \( v_{\text{the}} = \sqrt{2T_e/m_e} \). If toroidicity is ignored, the CD efficiency is largest when either \( x_e \gg 1 \), which minimizes collisional scattering of resonant electrons, or \( x_e \ll 1 \), which minimize the power expenditure per momentum transferred. In a tokamak, however, the latter option is not viable: to avoid degradation by toroidal trapping of the resonant electrons \( x_e \) cannot be much lower than unity, and the degree of degradation depends on the radial and poloidal localization of the RF power directly absorbed by electrons. The condition \( x_e \gtrsim 1 \) translates into a constraint on the toroidal wave number \( n_\varphi \),

\[
n_\varphi \lesssim \frac{f[\text{MHz}]}{3 \sqrt{T_e[\text{keV}]}} \frac{R_{\text{ant}}[\text{m}]}{R_{\text{ant}}} \tag{1}
\]

where we have approximated \( k_\parallel \) with its average value \( n_\varphi/R_{\text{ant}} \), and \( R_{\text{ant}} \) is the antenna distance from the torus axis. Finally, it is important to take into account that \( Z_{\text{eff}} \) has an important influence on the CD efficiency. In TORIC it is implemented the Ehst-Karney parametric formula for the CD efficiency [10].

Since the final goal is to maximize the driven current per unit of total coupled power, in addition to optimize the CD efficiency by an appropriate choice of the wave parallel phase velocity, it is essential also to maximize the fraction of the launched power deposited in the electrons. This is not trivial, because in the IC frequency range electron damping of the fast wave is a much weaker absorption mechanism than IC absorption by ions. At the high temperatures of an ignited plasma this is true even for relatively high IC harmonic resonances, and, in particular, for energetic alpha particles during slowing down, in spite of their great dilution. Windows of predominant electron absorption, therefore, can be found only when all IC resonances are either outside the plasma, or, at least, close to the inner plasma edge, well screened from the antenna by a large plasma layer in which only electron absorption can occur. As the position of these frequency windows depends sensitively on the value of the confining magnetic field, and to a lesser extent on the poloidal location of the launcher, it will be important to match accurately the antenna working range to the final DEMO design.

To maximize the fraction of power deposited in the electrons, it is also clearly desirable to increase as much as possible the strength of electron absorption in any plasma layer. Since the number of resonant electrons decreases exponentially as \( x_e \) decreases much below unity, this
poses a demand opposite to equation (1) on the antenna periodicity. Thus, the optimization of the total driven current will be a compromise between good electron absorption and high CD efficiency, which have opposite dependencies on $n_\phi$. This compromise is easier for power absorption by electrons peaked on axis, for which the trapping effects leading to condition (1) are less severe.

### Table 1. A few of the main parameters of DEMO1 and DEMO2 used in this analysis [2].

|                | $B_0$ [T] | $R$ [m] | $a$ [m] | $I_p$ [MA] | $q_0 / q_{95}$ | $n_{90} / (n_{90})$ [10^{19} m^{-3}] | $T_{90}$ [keV] | $Z_{eff}$ | $P_{fu}$ [GW] |
|----------------|-----------|---------|---------|------------|----------------|-----------------------------------|---------------|-----------|--------------|
| DEMO1 (pulsed) | 6.3       | 9.3     | 2.6     | 16.8       | 1.3/3          | 11.2/9.7                          | 30.7          | 3.76      | 2.8          |
| DEMO2 (steady-state) | 4.3       | 8.2     | 3       | 19.85      | 1.5/3.8        | 9.2/7.6                           | 37.1          | 3.26      | 2.1          |

### Figure 1. Temperature and electron density profiles for DEMO1 and DEMO2 and for both peaked and flat profiles. The background species are assumed to be in thermal equilibrium.

#### 3. ICRF scenarii and simulations with the full-wave TORIC code

The DEMO conceptual designs are obtained with an optimization procedure of some selected physics, engineering and economical quantities. Zero-dimensional systems codes that perform this optimization analysis, such as PROCESS [11], give the optimal values of a number of global scalar parameters. From these parameters we have calculated the magnetic equilibrium configuration using the Grad-Shafranov solver SPIDER [12] interfaced with the Astra transport code [13] for the density and temperature profiles. For this purpose SPIDER was executed in the “prescribed boundary” mode, with elongation and triangularity equal to 1.56 and 0.33 respectively, and with a parabolic $q$ (safety factor) profile. Using the transport model of Astra, the kinetic profiles have been iteratively optimized to match the values of fusion power and Greenwald fraction selected by the PROCESS. Since a key issue for DEMO is to mitigate the thermal load of the divertor plates, the present European DEMO designs have for this purpose a relatively high $Z_{eff}$. The values of $Z_{eff}$ in table 1 have been simulated by diluting the plasma with traces of iron in addition to 5% of He$^4$ ashes. To investigate the impact of density profiles in the plasma core while using the same equilibria, we have flattened the core density profiles while keeping unchanged the plasma pressure. The latter is achieved by rigidly rescaling the temperatures by a common local factor. The nominal (peaked) and flat profiles are shown in
figure (1) together with the corresponding temperature profiles. It is not pretended that the flat-density profiles are realistic.

Figure 2. (left) Red and blue lines are the fractions of RF power absorbed by electrons and α particles, respectively, as function of the frequency of the injected waves, in the case of DEMO1 with peaked density profiles. Symbols refer to three different values of \( n_\phi \) which are linearly scaled with frequency in order to keep constant \( x_e \). (right) Total driven currents.

Figure 3. Same of figure 2 for DEMO2 with peaked density profile.

To identify the possible frequency windows \([5, 6, 7]\) for these scenarii, preliminary frequency scans for three values of \( n_\phi \) are shown in figures 2 and 3. Since the critical parameter is \( x_e \) both for electron absorption and for CD efficiency, the frequency scan is performed by keeping constant \( x_e \). This implies that \( n_\phi \) is varied linearly with frequency. To show the dependence on \( x_e \), we have chosen three values of \( n_\phi \), chosen so that their values at 50 MHz were 25, 50, and 75: they are representative of the current spectrum of traditional multi-strap antennas. The symbols in figures 2 and 3 refer to these three values of \( n_\phi \). As shown in figure 2(right), when the frequency is lower than about 25 MHz, no ion cyclotron resonances are present inside the plasma, and electrons can absorb RF power without competing with ions. At these low frequencies it
is very difficult to obtain the required $n_{\varphi}$ values with traditional antennas. The next operative window is around 70 MHz, where only the first harmonic of the tritium, $\omega = 2\Omega c_T$, falls inside the plasma far on the high field side. Other operative windows are present at higher frequencies starting from 110 MHz. At higher frequencies, however, the RF power absorbed by $\alpha$ particles is not negligible. In DEMO1 at 110 MHz, for example, with $\omega = 2\Omega c_{\alpha}$ close to the magnetic axis, absorption by $\alpha$ is reduced by placing the launcher in the upper or lower part of the outer vessel, far from the equatorial plane, to avoid that RF waves impinge the $\alpha$ IC resonance [6, 7]. Figures 2(right) and 3(right) show the corresponding driven currents. As anticipated, the power $P_e$ absorbed by the electrons increases with increasing $n_{\varphi}$. At the same time the CD efficiency decreases with $n_{\varphi}$, mainly because of toroidal trapping, and as a consequence the total driven current actually decreases with increasing $n_{\varphi}$. Similar considerations hold for DEMO2 when the frequencies are rescaled by about the ratio of the magnetic fields, as shown in figure 3.

**Figure 4.** Total driven current as function of the toroidal periodicity of the antenna with two (circle) and four straps (square) (left: DEMO1 at 70 MHz - right: DEMO2 at 55 MHz). The solid and dashed lines are respectively for peaked and flat density profiles (figure 1). For comparison, the same quantities are shown for a lower value of $Z_{\text{eff}}$, namely 1.58. The left axis shows the same values in terms of $\gamma_{\text{CD}}$. In all these runs, the antenna phasing $\Delta \phi$ is set to $\pi/2$.

4. The role of the antenna
The total amount of FWCD is the result of an interplay among several effects, which in turn depend on plasma and antenna parameters. Therefore, an estimate of the total driven current requires a model of the ICRF launchers. If we rely on simple models of traditional multi-strap antennas, the relevant antenna parameters are the toroidal periodicity, $w + d$ with $w$ the width and $d$ the distance of the straps, the number of straps, $N_g$, and the relative phase of the currents flowing in neighboring straps, $\Delta \phi$. The Fourier spectrum of the antenna currents has the main peak centered around $\hat{n}_{\varphi}$ and of width $\Delta \hat{n}_{\varphi}$ given approximatively by

$$\hat{n}_{\varphi} \approx \frac{R_{\text{ant}}}{w + d} \Delta \phi,$$

$$\Delta \hat{n}_{\varphi} \approx \frac{2\pi}{N_g(w + d)} \Delta \phi$$

where we have assumed that $\Delta \phi$ is equal for all neighboring straps. The power spectrum of the wave fields inside the plasma is affected by the presence of an evanescence layer between
the antenna and the low-density cutoff layer [14]. This evanescence layer works as low-pass $n_\phi$ filter, which tailors the antenna spectrum by cutting the high $n_\phi$ part of the spectrum. As a consequence, the main peak of the field spectrum is shifted towards values somewhat lower than $\hat{n}_\phi$ of equation (2). We also recall that the launched $k_\parallel$ spectrum is further broadened by the fact that each poloidal Fourier component has a different $k_\parallel$: in all our simulations the poloidal wavenumber spanned the range $-31 \leq m_\vartheta \leq +31$. Both these effects are automatically taken into account in TORIC.

Finally, increasing the number of straps $N_g$ improves the directionality of the antenna and increases the driven current; this number, however, is limited by the available access and by the fact that to control the phases each strap must be individually fed. Figure 4 shows how the total driven current varies with $(w + d)$ and $N_g$ for DEMO1 (left) and DEMO2 (right). In figure 4 the trend of $I_{RF}$ with $(w + d)$ can be understood by taking into account also the dependence on $(w + d)$ of the fraction of RF power absorbed by electrons shown in figure 5. At 70 MHz in DEMO1 and 55 MHz in DEMO2 the electrons suffer competition only by tritium with its first IC harmonic on the high field side. Electron absorption is larger in DEMO2 because of the higher $T_e$. For both DEMO1 and DEMO2 the results obtained with flat profiles show on average higher total driven current: this is again due to the higher $T_e$ necessary to balance the density flattening in order to keep constant the plasma pressure and the pedestal. To explore

| DEMO1 | DEMO2 |
|-------|-------|
| $N_g = 4$ | $N_g = 8$ |
| $Z_{eff}=1.58$ | $Z_{eff}=2.78$ |

**Figure 5.** Power absorbed by electrons for the cases considered in figure 4.

the sensitivity of CD efficiency on $Z_{eff}$, we have considered $Z_{eff} = 1.58$, which is lower than the values of table 1, and closer to the values used in [5, 6, 7, 4, 15]. For this purpose, we have reduced the iron concentration, which entails also an increase of deuterium-tritium fuel and thus of $\alpha$ particles. As expected, the total driven current with the lower value of $Z_{eff}$ is systematically higher than $I_{RF}$ with higher $Z_{eff}$.

For completeness, figure 6 shows the driven currents $I_{RF}$ for a low frequency scenario ($f \lesssim 20$ MHz). These values are comparable with those of figure 4, although at these low frequencies the RF power is mainly absorbed by electrons. However, if the antenna parameters are kept unchanged, the CD efficiency decreases with frequency, since $x_e$ decreases. Finally, figure 7 shows how $I_{RF}$ varies with the antenna phasing $\Delta \phi$. In DEMO2 the highest predicted $I_{RF}$ is around $\Delta \phi \approx 60^\circ$ (figure 7(right)), lower than $90^\circ$ where one expects the highest antenna directionality, as it is for DEMO1 (figure 7(left)). Also in this case, the sensitivity of the amount of RF power absorbed by electrons on $n_\phi$ plays a major role on $I_{RF}$. To allow a
straightforward comparison with other CD systems, in figure 4, 6, and 7 the left ordinate axis reports the corresponding values of the global figure of merit $\gamma_{CD}$ defined as

$$\gamma_{CD} = \langle n_e \rangle [10^{20} \text{m}^{-3}] \frac{R_0 [\text{m}]}{P_{\text{RF} [\text{W}]}} I_{\text{RF} [\text{A}]}$$

with $\langle n_e \rangle$ the volume-average density. The $\gamma_{CD}$ values are in the same range as those predicted for EC [15] and for NBI CD at low $Z_{\text{eff}}$ [4].

5. Discussion

Our simulations for the two presently proposed DEMOs show that the performances of a FWCD system will substantially depend not only on plasma parameters but also on the antenna
geometry. With an antenna located at mid plane on the low-field side detrimental absorption by fusion-born $\alpha$ particles can be avoided at very low frequencies ($f \lesssim 20$ MHz) and in a window at intermediate frequencies, 70 MHz for DEMO1 and 55 MHz for DEMO2. For low values of $Z_{\text{eff}}$ and for reasonable antenna parameters, the values of $\gamma_{\text{CD}}$ are comparable with those of other current drive systems [4], provided the antenna spectrum is opportunistically tailored. Since absorption by electrons is strongest in the plasma core where the electron temperature is higher, and reduction of the efficiency by toroidal trapping of resonant electrons is also weakest near the magnetic axis, FWCD is most efficient for on-axis CD [16]. Thus, FWCD seems to be insufficient to replace the ohmic contribution to off-axis current profile, and it must be complemented with an other CD system [4]. Undesirable synergies must also be taken into account: for example, in the presence of simultaneous NBI a reduction of FWCD performances might occur as a non negligible fraction of the RF power can be efficiently absorbed by the fast ions born from NBI neutrals [17].

FWCD in the range of frequencies considered in this study is presently the only CD method for which reliable, robust and economically appealing sources already exist. The critical element of an ICRF system will be the antenna. Nevertheless, many of the important issues in antenna design, including optimization of coupling and electron absorption, avoidance of parasitic absorption in the scrape-off plasma and sputtering in passive elements and the wall, can already be further investigated in present devices, in which the frequencies used are in the same range as those proposed for FWCD in DEMO [5, 6, 7, 16].

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