Potential of fast wave ICRF current drive in DEMO plasmas

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Introduction According to the present fusion roadmap, a demonstration of electricity production by a thermonuclear fusion power plant DEMO should be established by 2050 [1]. For the continuous operation of future tokamak-reactors or for extending plasma duration in case of pulsed operation, a non-inductively driven toroidal plasma current is essential. The bootstrap current due to the pressure gradient and current driven by auxiliary heating systems are considered as the two relevant options for this task. In this paper, we discuss the current drive (CD) potential of the ion cyclotron resonance frequency (ICRF) heating system in DEMO-like plasmas. Fast wave (FW) CD scenarios are evaluated for the standard mid-plane launch and for the alternative option that relies on exciting the waves from the top of the machine. Optimal ICRF frequencies and FW parallel wave numbers are identified to maximize the CD efficiency, which is shown to be comparable to those predicted for the negative neutral beam injection (NBI) and electron cyclotron resonance heating.

FWCD potential for the standard launch ICRF heating has been used successfully for bulk ion and electron heating in present-day tokamaks, and it is one of the systems considered for installation in ITER and DEMO. Among the systems used for heating fusion plasmas, ICRF has a number of advantages: high wall plug efficiency and low cost per MW of generated power, possibility to ensure central heating and current drive (H&CD) as the FW has no high-density limits, and availability of the technologies for generators and antennas. Finally, ICRF is the only system capable of delivering a significant fraction of the power to thermal ions [2], which will help in reaching the ignition point. The main challenge for the ICRF system in the next-step tokamaks is the coupling of the RF power from the antenna to the plasma because of the large evanescence layer gap, and optimization of ICRF coupling is an ongoing issue [3].

As input for ICRF modelling, we use parameters close to those for DEMO2, which is an advanced concept aiming at steady-state tokamak operation [4]. The DEMO machine will be larger than ITER ($R_0 = 8.152$ m and $a = 2.982$ m), and will operate at higher densities and temperatures, $n_{e0} = 1.0 \times 10^{20}\ \mathrm{m}^{-3}$ and $T_{e0} = 30.9$ keV (the thermal population of ions is assumed to have the same temperature as electrons). The profile exponents for the density and temperature are taken as $\alpha_n = 0.3$ and $\alpha_T = 1.0$, which correspond to the ratio of the volume averaged to the central value $\langle n_e \rangle / n_{e0} \approx 1/1.3$ and $\langle T_e \rangle / T_{e0} \approx 1/2.0$, respectively. The toroidal magnetic field for DEMO2 is $B_0 = 5.043$ T and the envisaged plasma current is $I_{\mathrm{pl}} \approx 20$ MA. One half of the latter is computed to be due to the bootstrap current and the second half is to be generated by the H&CD systems.

We consider a balanced D-T fuel mix, including 1.0% of high-energy alpha particles and 10.0% of thermalized alphas (helium ash), 0.3% of fast deuterium ions born due to NBI heating, 2.0% of beryllium impurity ions and 0.1% of helium-3 ions. Quasineutrality of the plasma implies that $X[\mathrm{D}] = X[\mathrm{T}] = 34.75\%$. This corresponds to the effective charge state $Z_{\mathrm{eff}} = \sum_i n_i Z_i^2 / n_e \approx 1.5$. Fast ion populations are modelled by an equivalent Maxwellians with an effective temperature 1.12 MeV for alpha particles and 400 keV for the D beam [5]. Note that a higher $Z_{\mathrm{eff}} = 3.3$ was considered for DEMO2 in [4]. Though its value has a marginal impact on the FW propagation and absorption, it does have an effect on the CD efficiency via the plasma collisionality. For higher operational values of Z_{eff}, the FWCD efficiency is lower.

The standard ICRF heating technique is based on launching the FW by the antenna located at the low field side (LFS) edge of the plasma. As the wave propagates from the edge to the plasma core, it is partially absorbed by electrons due to ELD/TTMP damping and is commonly efficiently absorbed by ion species, when the wave crosses the ion cyclotron (IC) resonance layers. At the resonance layers the wave frequency $\omega = 2\pi f$ (f is the ICRF driver frequency) matches the fundamental or harmonics of the cyclotron frequency for ion species, $\omega = N\omega_{ci} = N(q_i B/m_i)$, where B is the local magnetic field strength, q_i and m_i are the charge and the mass of the resonant ions, and N is the cyclotron harmonic number $(N = 1, 2, ...)$.

FWCD relies on electron absorption, and hence driving the toroidal non-inductive current requires tuning the ICRF system to ensure most of the RF power to be directly absorbed by electrons rather than ions. Since the expected temperatures envisaged for DEMO are much higher than those reached in the present-day tokamaks, IC damping of the wave in DEMO is expected to be very efficient for the baseline operation conditions and care should be taken to allow channelling a higher fraction of the RF power to electrons. Therefore, for the standard midplane launch one should select an ICRF frequency avoiding IC resonances located on the LFS. Figure 1 shows the location of the resonance layers in the plasma for bulk ion species as a function of the ICRF frequency. Two frequency windows are feasible to meet the criteria of eliminating LFS ion absorption (green arrows): $f \approx 50$ MHz and 80 MHz. For example, operating at $f = 51$ MHz allows to place the $\omega = 2\omega_{cD}$ resonance out of the plasma, whilst keeping the $\omega = 2\omega_{cT}$ resonance in the center.

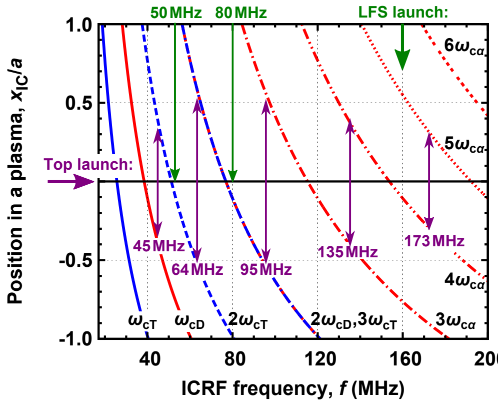

Figure 1: Location of the IC resonance layers for bulk ion species as a function of the ICRF frequency ($B_0 = 5.043$ T).

This choice of frequencies is confirmed by the simulations with the full-wave code TORIC [6]. Once the RF frequencies are identified, the proper FW parallel wave numbers to be excited by the ICRF antenna are computed to optimize the CD efficiency. The latter is evaluated using the well-established Ehst-Karney (EK) parametrization [7]. Figure 2(a) shows the integrated CD efficiency $\hat{I}_{\rm CD}$ (current driven per unit of ICRF power coupled to the plasma) as a function of the FW toroidal wave number $n_{\rm tor}$ ($k_{\|} \simeq n_{\rm tor}/R$). Though the fraction of RF power absorbed by electrons is the largest at $n_{\rm tor} = 47$, for maximizing CD it is beneficial to operate at lower $n_{\rm tor} = 24$. Then, the FW is less efficiently absorbed by electrons ($f_e \approx 62\%$), but the power is deposited closer to the center (Fig. 2(c)), which favours achieving higher $\hat{I}_{\rm CD} \approx 35$ kA/MW. For the LFS equatorial launch and the usual frequency range, an upshift/downshift of $k_{\|}$ due to the poloidal magnetic field is scarcely important and the curves evaluated for two opposite directions of the plasma current almost coincide. The analysis of the radial profile of the driven current (Fig. 2(b)) shows that 90% of the generated current is driven centrally, within $0 \leq \rho \leq 0.5$. At higher ICRF frequencies $f > 80$ MHz, the FWCD is inefficient since most of the RF power is absorbed by energetic alpha particles at their higher harmonics ($\omega = 3\omega_{c\alpha}$, $\omega = 4\omega_{c\alpha}$, etc.).

FWCD potential for the top launch Parasitic alpha particle heating is the main competitor for electron absorption, in particular at high frequencies. The top launch idea is based on the fact that IC resonance layers are crudely aligned with $R = const$ surfaces, so that launching waves *in between* the regions where alpha heating is efficient (by placing the antenna at the top rather than near the equatorial plane of the machine) is likely to enhance the potential of electron FWCD [8].

For the top launch, the ICRF frequencies should be selected such that the IC resonant layers are absent in the center of the plasma. This is shown with the purple arrow in Fig. 1, and the proper ICRF frequencies are also highlighted. They can be determined via $f_n({\rm MHz}) \approx 3.8\,(2n-1)\,B_0({\rm T})$, where n is an integer. If operating at the frequency f_n, two adjacent IC layers for alpha particles are equidistantly located from the magnetic axis: $\omega = n\omega_{c\alpha}$ on the LFS and $\omega = (n-1)\omega_{c\alpha}$ on the HFS. This yields $f = 96$ MHz/135 MHz/173 MHz/211 MHz, etc. for $n = 3, 4, 5, 6, ...$ One should note here that for high frequency operation, the distance between two adjacent resonance layers for alphas decreases with the wave frequency f_n and n, $\Delta R = R_0/(n-1/2)$. For $n = 2$, the frequency should be somewhat higher ($f = 64$ MHz, $\Delta R = 2R_0/5$) because of the $\omega = 2\omega_{cT}$ layer on the HFS. There is an additional acceptable frequency ($f = 45$ MHz), for which the $N = 2$ tritium layer is located on the LFS, while the fundamental resonance for deuterium and alphas is on the HFS. For this frequency $\Delta R = 2R_0/7$, which is smaller than the distance between the IC layers for 64 MHz and 96 MHz.

Figure 2(d) shows the $n_{\rm tor}$–dependence of the CD efficiency computed for $f = 61$ MHz. The integrated driven current is higher for the top launch and reaches $\hat{I}_{\rm cd} \approx 45-50$ kA/MW, depending on the direction of the plasma current w.r.t. the toroidal magnetic field. The optimal $n_{\rm tor}$ is different for $\pm I_{\rm pl}$ due to the upshift/downshift of $k_\parallel$, which it undergoes accounting for a finite poloidal magnetic field. The radial profile of the generated current is also somewhat different to that for the LFS launch case: $\sim 80\%$ of the current is driven within $0.2 \leq \rho \leq 0.6$ (Fig. 2(e)). For the considered conditions, 86% of the RF power is absorbed by electrons, and the corresponding absorption profile is depicted in Fig. 2(f).

By keeping fixed $k_\parallel$ and increasing the ICRF frequency, the parameter $w = \omega/(k_\parallel v_{te})$, which determines the CD efficiency, grows. This potentially allows to drive more current since one of the terms in the EK formula is proportional to w^2. However, at low $k_\parallel$ and large w the single-pass absorption (SPA) by electrons is small ($f_e \propto we^{-w^2/2}$). Thus, the wave will undergo multiple bounces within the plasma before being fully absorbed and, eventually, it will cross the IC resonant layers of the alpha particles. Increasing $k_\parallel$ at higher ICRF frequencies to improve the SPA will result in a lower w–value and reduced CD efficiency. Another limiting factor for the high frequency top launch operation is the reduction of the distance between the adjacent $\omega = N\omega_{c\alpha}$ layers that will impose constraints on the antenna size.

Analytical estimate of the maximum FWCD efficiency Assume that all RF power is deposited at a single point of the plasma cross-section. Then, the absorbed power density can be written as $p_{\rm abs}(r,\theta) = p_{00}\delta(r-r_0)\delta(\theta-\theta_0)$, where $\delta(x)$ represents the Dirac delta function and p_{00} is the normalization constant for the power density. We consider f_e to be the fraction of the RF power absorbed by electrons and therefore contributing to the driven current. The local CD efficiency $\eta_{\rm CD} = j_{\rm CD}/p^{(e)}_{\rm abs}$ (the ratio of the driven current density to the deposited power density) is described by the EK formula: $\eta_{\rm CD} = \eta^*\eta_0 f_{\rm neo}$, where η^* is the normalization constant, η_0 is the homogeneous (dimensionless) CD efficiency, and $f_{\rm neo} \leq 1$ is the neoclassical correction factor due to the particle trapping effect [7]. The function $f_{\rm neo}$ depends on the poloidal angle and the local aspect ratio and decreases when the RF power is absorbed more off-axis. The homogeneous CD efficiency $\eta_0(w, Z_{\rm eff})$ can be uniformly approximated by the expression $\eta_0 \approx 20.3/(Z_{\rm eff}+0.9) + 1.4(w-1.7)^2$, which is valid for $1 \leq Z_{\rm eff} \leq 3$ and $1 \leq w \leq 3$. Therefore, the integrated driven current can be estimated as follows

$$\hat{I}_{\rm CD} \approx f_e \frac{0.068\, T_e(\text{keV})}{n_{e,20}(Z_{\rm eff}+0.9)R_0} f_{\rm neo}. \tag{1}$$

For $Z_{\rm eff} = 1.5$ and total central electron absorption ($f_{\rm neo} = 1$ and $f_e = 100\%$), Eq. (1) predicts $\hat{I}_{\rm cd} \approx 0.10$ A/W, which is the upper limit for the CD efficiency that may be reached for the considered parameters. For the LFS launch – though the driven current density peaks at the center – there is a significant current driven within $0.1 \leq \rho \leq 0.4$, as follows from Figs. 2(b) and (c). The averaged value for the neoclassical factor for such radii is $f_{\rm neo} \simeq 0.7$. Accounting for the fact that for the LFS launch $f_e \approx 62\%$, the driven current would be lowered to 0.045 A/W, which is in good agreement with the value calculated numerically. Though for the top launch RF power is absorbed at larger radii, the neoclassical correction does not change much because the power is deposited at the different poloidal angles, $\theta \simeq \pi/2$. Thus, higher CD values for the top launch are mainly due to higher fraction of power absorbed by electrons: for conditions of Fig. 2(f) $f_e \approx 86\%$, which is 1.4 times larger than that for the LFS launch.

Conclusions The ICRF fast wave current drive efficiency has been evaluated for DEMO2 plasmas, and optimal RF frequencies and FW parallel wave numbers have been identified numerically. For the standard LFS launch, the CD efficiency is computed to be $\hat{I}_{\rm cd} \approx 0.035$ A/W, and most of the current is shown to be generated close to the plasma center. For the top launch, higher CD efficiencies can be obtained, $\hat{I}_{\rm cd} \approx 0.045 - 0.050$ A/W, and the generated current profile is peaked at $\rho \simeq 0.4$. These values are computed for $Z_{\rm eff} = 1.5$. The CD efficiency is shown to reduce with $Z_{\rm eff}$, viz. $\hat{I}_{\rm cd} \propto 1/(Z_{\rm eff} + 0.9)$. High-frequency FWCD operation ($f = 100 - 200$ MHz) is hampered by parasitic absorption of RF power by alpha-particles and limited single-pass absorption.

Computed values of the FWCD efficiency are on a par to those predicted for other heating systems considered for DEMO. For example, in Ref. [9], $\hat{I}_{\rm cd} = 11.3/250 \approx 0.045$ A/W was calculated for 1.5 MeV negative ion beams and $\hat{I}_{\rm cd} = 10.4/293 \approx 0.036$ A/W – for 270 GHz ECRF system. The results of our studies confirm that ICRF heating, aside from its relevance for pre-heating the plasma to fusion-relevant conditions, is a competitive candidate for non-inductive current drive in high temperature fusion reactors such as DEMO.

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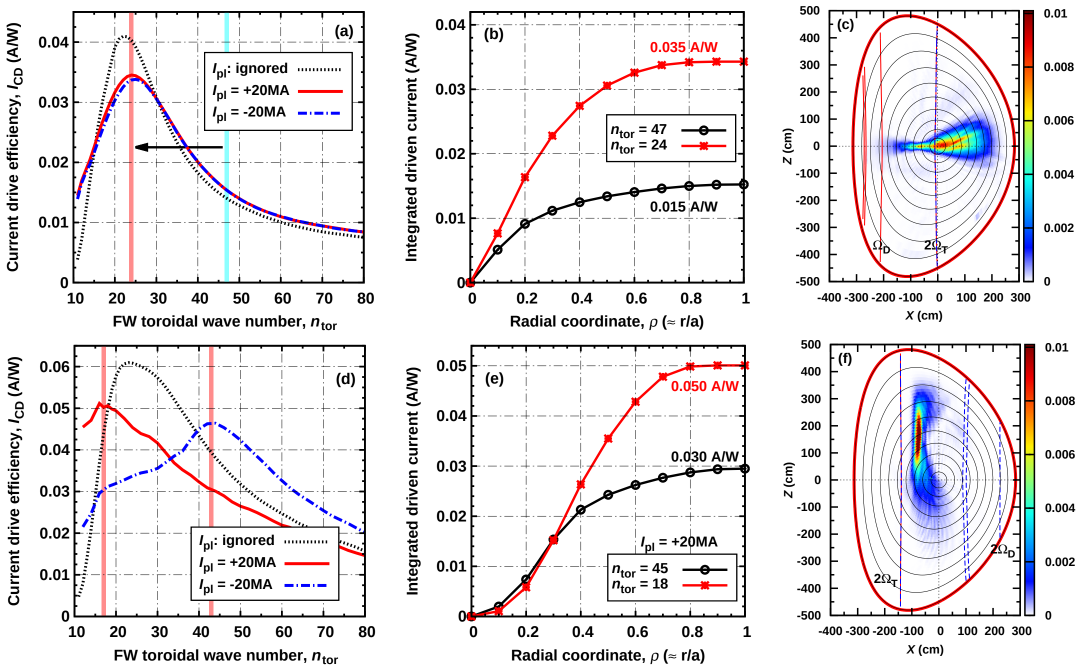

Figure 2: Top row figures are computed for the LFS launch ($f = 51$ MHz), and bottom row for the top launch ($f = 61$ MHz). (a,d) CD efficiency vs. $n_{\rm tor}$; (b,e) Radial profile of the integrated driven current; (c,f) 2D profile of the power deposition to electrons for $n_{\rm tor} = 24$ and 18.

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