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R. Koch, E. Lerche, D. Van Eester, and M. Nightingale

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High frequency fast wave current drive for DEMO

R.Koch[1], E.Lerche[1], D.Van Eester[1], M. Nightingale[2]

[1] *LPP/ERM-KMS, Association "EURATOM-Belgian State", 1000 Brussels, Belgium, TEC Partner*
[2] Culham Centre for Fusion Energy, Abingdon OX14 3DB, United Kingdom

Abstract. A steady-state tokamak reactor (SSTR) requires a high efficiency current drive system, from plug to driven mega-amps. RF systems working in the ion-cyclotron range of frequencies (ICRF) have high efficiency from plug to antenna but a limited current drive (CD) efficiency and centrally peaked CD profiles. The latter feature is not adequate for a SSTR where the current should be sufficiently broad to keep the central safety factor (possibly significantly) above 1. In addition, the fact that the fast wave (FW) is evanescent at the edge limits coupling, requiring high voltage operation, which makes the system dependent on plasma edge properties and prone to arcing, reducing its reliability. A possible way to overcome these weaknesses is to operate at higher frequency (10 times or more the cyclotron frequency). The advantages are: (1) The coupling can be much better (waves propagate in vacuum) if the parallel refractive index $n_{//}$ is kept below one, (2) The FW group velocity tends to align to the magnetic field, so the power circumnavigates the magnetic axis and can drive off-axis current, (3) Due to the latter property, $n_{//}$ can be upshifted along the wave propagation path, allowing low $n_{//}$ launch (hence good coupling, large CD efficiency) with ultimately good electron absorption (which requires higher $n_{//}$). Note however that the $n_{//}$ upshift is a self-organized feature, that electron absorption is in competition with α-particle absorption and that uncoupling of the FW from the lower hybrid resonance at the edge requires $n_{//}$ slightly above one. The latter possibly counterproductive features might complicate the picture. The different aspects of this potentially attractive off-axis FWCD scheme are discussed.

Keywords: Fusion reactor, DEMO, ICRH, current drive
PACS: 28.52.Cx, 52.40.Fd, 52.50.Qt, 52.55.Wq

BACKGROUND

There are presently several concepts of DEMO's envisaged. The first one is a pulsed machine requiring (from the tokamak design and operation viewpoint) only a modest extrapolation from ITER. The second one is a stationary-state tokamak where about 60% of the current needs to be driven by external means (i.e. non-ohmic). A third one is an 'advanced' stationary-state tokamak where most of the plasma current is bootstrap current. In this paper, we consider the second case, where a large amount of current drive (typically 56% of a total plasma current of I_p = 23 MA [1]) has to be provided by auxiliary systems. This current needs to be generated as efficiently as possible to minimize the recirculating power and hence the cost of electricity. Earlier studies [1] based on a model of neutral beam current drive (NBCD) assuming a CD efficiency $\gamma = n_e R_0 I_{CD} / P_{CD}$ (R_0 major radius, I_{CD} auxiliary driven current and P_{CD} corresponding CD power, all units SI except plasma density n_e in 10^{20}m^{-3}) of 0.5 led

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to an estimate of 200 MW of CD power, which taking into account an estimated system efficiency of 0.6 leads to a wall plug power of some 350 MW for a 1 GW electric plant power. In order to keep the central safety factor below one, the driven profile of the current has to be broad, i.e. a substantial fraction of it has to be driven off-axis. There exists presently no system able to meet these requirements. The NBCD estimates assume an injection energy of 1.5 MeV and the ability to drive large currents off-axis, which is presently speculative [2]. Off-axis electron cyclotron CD has a low efficiency due to banana trapping of electrons and efficient sources are still under development. Conventional – i.e. around or below the first few cyclotron harmonics - fast wave current drive (FWCD) seems able to meet the efficiency requirements [3], thanks to very good technical system efficiency, but generates only peaked current profiles. Given this situation, it is proposed to widen horizons and to look for alternative systems fitting better the stationary DEMO needs.

DRIVING OFF-AXIS CURRENT WITH THE FW

One obvious way to drive off-axis current with the FW is to use mode conversion to the ion-Bernstein wave. However, with low field side (LFS) launchers the wave has to cross the D cyclotron resonance and an evanescence layer before reaching it. The conversion efficiency is therefore uncertain and the control of the direction in which the current is driven might be an issue. If high field side launch would be possible high efficiency CD would probably be achievable, but the compatibility of such launchers with reactor design is uncertain.

A second possibility, which we investigate here, is to exploit the propagation properties of the FW in the high harmonics frequency range. The tendency of the FW to align to the magnetic field direction is illustrated by Fig.5 of ref. [4] obtained by ray-tracing. It shows that in the higher harmonics range, the group velocity is no longer parallel to the phase velocity and that a ray launched normally to the plasma surfaces tends to align to the magnetic surfaces and to circle around the plasma centre. This can lead to off-axis current drive deposition. In order to maximize the current drive efficiency, power should be transferred to electrons at the highest possible normalized phase velocity, i.e. $w = v_{ph}/V_{th} \equiv (\omega/k_{//})/\sqrt{k_B T_e/m_e} \gg 1$ (ω is the angular frequency, $k_{//}$ the parallel wavenumber, k_B Boltzmann's constant and T_e and m_e the electron temperature and mass). This requirement conflicts with that for good electron absorption, which requires $w \approx 1$. How these antagonistic requirements compete is sketched in Fig.1, where the current drive efficiency taken from ref. [5] is compared with the electron absorption strength indicating that a trade-off between the two processes should occur for $w \approx 2$. Actually, the analysis of ref. [6] at 20 and 200 MHz, which also takes into account the competing mechanism of bulk ion absorption, indicates that the optimum should rather lie around $w \approx 3$.

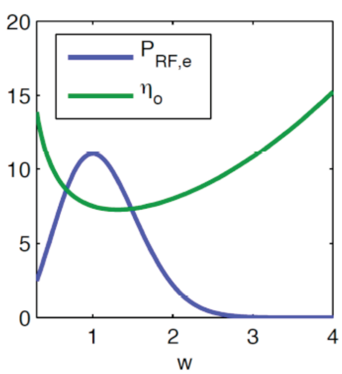

FIGURE 1. Current drive efficiency (η_0) and electron power absorption (P_{RFe}) versus relative wave phase velocity w

COMPETITION WITH FAST ION DAMPING (FIRST ESTIMATES)

However, the main competitor to electron damping is absorption by fast α's or beam-injected ions and was not taken into account. At high cyclotron harmonics, damping is larger for faster particles, which is potentially as or more important than bulk ion absorption, even though cyclotron absorption strength decreases with harmonic number. A complete full-wave description of electron absorption in presence of fast

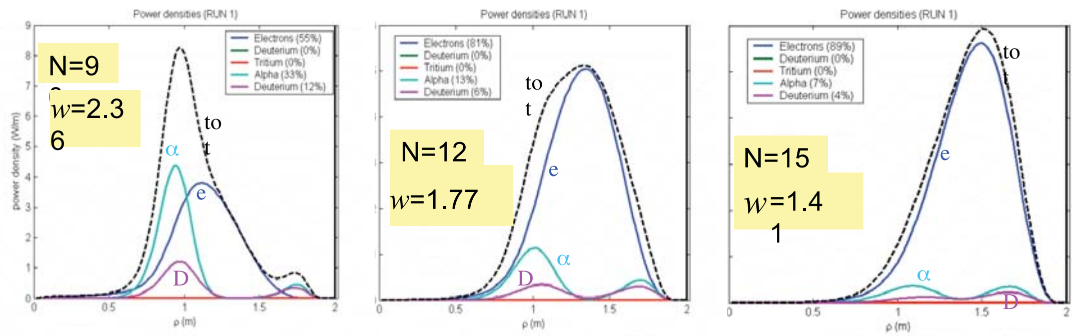

FIGURE 2. TRIANGLES runs. Power deposition profiles on the different plasma species versus minor radius for 250 MHz and three values of the toroidal mode number N

ions should incorporate both cyclotron absorption by the non-maxwellian slowing-down populations and the poloidal field effects. The latter can be very important as the fast ion density (especially α's) tends to be very peaked. If the wave turns and damps out of the plasma centre where the fast ion density is lower, fast particle absorption can be reduced as compared to the no poloidal field case. The preliminary results from TRIANGLES [7] presented below do not include this poloidal field effect. They also do not take into account a real slowing down distribution of fast particles but assume a maxwellian with temperature 1.12 MeV for α particles [8] and 0.4 MeV for the fast D ions from NBCD. Finally, note that these computations are done for a slightly upgraded ITER (B_0=5.3T, I_p=15MA, R_0=6.2m, a_p=2m, n_{e0}=10^{20}m^{-3}, T_0=25keV) and that all density profiles are flat (parabolic to power 0.1), including fast particle ones. All these choices are rather pessimistic as compared to realistic full-size DEMO conditions. A last word of caution: due to the very small wavelength of the FW at high frequency, most of the runs of TRIANGLES are done at the limit of its present capabilities and are not fully converged. As an example of the results, Fig.2 shows the variation of the

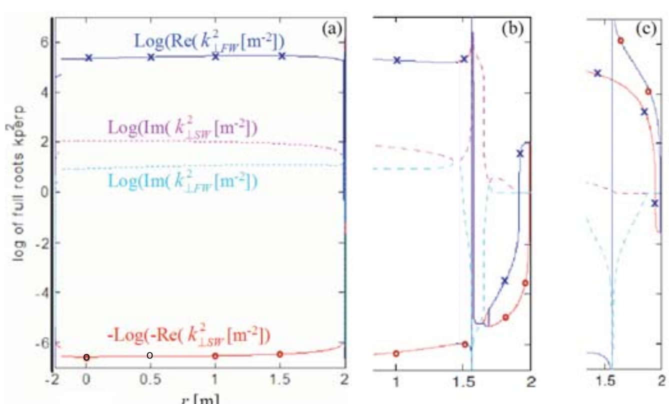

FIGURE 3. Slow (o) and fast (x) wave dispersion at LFS for f = 500MHz. (a) Flat density profile (parabolic)$^{0.3}$ and $k_{//}$=3.65 m^{-1}, (b) Peaked density profile (parabolic)^2, same $k_{//}$, (c) same as (b) but $k_{//}$=12 m^{-1}.

distribution of the power deposited among the different species at 250 MHz when the toroidal mode number is varied. The conclusion from this and the 150 MHz (not shown) cases seems to be that to avoid excessive competition from fast particles a *w* around 1.4 or lower is required for the chosen parameters.

COUPLING

Fig.3 shows the two roots of the cold plasma wave dispersion relation near the LFS edge of the plasma. In (a), the dispersion looks regular except at the very edge of the plasma. To zoom on this effect, a very peaked density profile is used in (b). This spreads the low density region and shows that for a spectrum typical of the present ITER antenna, the FW couples to the lower hybrid (LH) resonance. At the very edge of the plasma, both SW and FW become evanescent and confluent because the lower hybrid is not "accessible". From our point of view of launching the FW, this is potentially harmful as it can lead to spurious absorption of the FW at the edge. The condition for LH waves accessibility is $n_{//}^2 = (ck_{//}/\omega)^2 > n_c^2 = 1/(1-\omega^2/|\omega_{ce}\omega_{ci}|) \approx 1$. This is shown as case (c) corresponding to higher $k_{//}$ where the FW and SW are completely uncoupled, but the FW has a now a limited evanescence zone at the edge.

CONCLUSIONS

The present preliminary study shows that although there is a potential way, at high frequency, to generate off-axis current with the FW, the conditions for efficient current generation, good electron absorption and low absorption by fast ions, requiring moderately high $k_{//}$ in the absorption zone, are conflicting with the requirements of good coupling, which requires $k_{//}$ slightly above but close to the vacuum value $k_0 = \omega/c$. A possible way of solving this problem is to uncouple the two requirements by launching waves at low $k_{//}$ for good coupling but such that they would propagate around the plasma center, get a self-consistent $k_{//}$-upshift and generate current with high efficiency until *w* gets near 1 at which point they should be completely absorbed by strong electron damping. In case the physics would validate this concept, design of a proper launcher, identification of an adequate power source and experimental test on a relevant tokamak would remain to be performed.

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