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RF H&CD Systems for DEMO – Challenges and Opportunities

T. Franke[1,2], E. Barbato[5], A. Cardinali[5], S. Ceccuzzi[5,6], R. Cesario[5], D. V. Eester[3], E. Lerche[3], M.-L. Mayoral[1,4], F. Mirizzi[5], M. Nightingale[4], J.-M. Noterdaeme[2], E. Poli[2], A. A. Tuccillo[5], R. Wenninger[1,2] and H. Zohm[2]

[1]*EFDA Close Support Unit, Boltzmannstr. 2, D – 85748 Garching, Germany*
[2]*Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, D - 85748 Garching, Germany*
[3]*Association EURATOM-Belgian State, LPP-ERM/KMS, TEC partner, Brussels, Belgium*
[4]*Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[5]*Associazione Euratom-ENEA sulla Fusione, C.P. 65-I-00044-Frascati, Rome, Italy*
[6]*Applied Electronics Department, Roma Tre University, Via della Vasca Navale, 84 00146, Roma, Italy*

Abstract. The aim of driving a sufficient amount of plasma current with an appropriate radial current density profile is considered as one of the key challenges for a tokamak fusion power plant in steady state operation. Furthermore, efficient heating to enable transition to regime of enhanced confinement and to achieve breakeven plasma temperatures as well as MHD control and plasma breakdown assistance are required. In the framework of the EFDA Power Plant Physics and Technology (PPPT) activities, the ability of the Electron cyclotron (EC), Ion Cyclotron (IC) and Lower Hybrid (LH) systems to fulfil these requirements, was studied for a demonstration fusion power plant (DEMO). As boundary condition, a 1D description of the plasma for a pulsed DEMO based on system code studies combined with transport analysis was developed. The predicted 1D plasma parameters were used to calculate the current drive (CD) efficiency of each system and eventually optimised it. As an example, the EC current drive efficiency could be increased strongly by top launch compared to equatorial launch at least by a factor of two. For the IC system, two possible windows of operation for standard and higher frequencies were highlighted, whereby again top launch leads to higher CD-efficiencies. The efficiencies predicted for DEMO for the RF current drive systems will be presented. Finally, gaps in the feasibility of RF systems under DEMO relevant conditions will be identified.

Keywords: Tokamak, DEMO, Current Drive Efficiency, ECCD, ICCD, LHCD, FWCD.
PACS: 52.55.Wq, 52.35.Hr, 52.35.Qz, 52.50.Qt

INTRODUCTION

RF systems are potential candidates for DEMO to perform heating and current drive (H&CD). In the framework of the EFDA PPPT work programme 2012 the CD efficiencies of common H&CD RF systems were investigated. Since the CD efficiency is of particular interest to predict the performance of DEMO (net electric power, burn time, cost of electricity etc.) the work was carried out on physics and technological aspects. Only the physics results are presented in this paper. Further to existing studies and calculations [1-3] the aim of the work was to improve the CD efficiency. Note that, in general the CD performance of H&CD systems can be specified as a product of efficiencies (electricity conversion at the source, power transmission to the vessel ports, RF wave absorption of the plasma and CD efficiency). This defines, in combination with RAMI (reliability, availability, maintainability and inspectability) of the subsystems, the performance and usability of the RF H&CD systems for DEMO.

PREREQISITES FOR CURRENT DRIVE CALCULATIONS

The first assumptions to be made were on the kinetic profiles. Reference profiles were established in order to evaluate in a comparable manner the overall performance of each H&CD system, i.e. EC, IC and LH systems (as well as Neutral Beam, which as non-RF system is not discussed in this paper). The starting 0D parameters used for DEMO1, which is within EFDA defined as a pulsed, but not a steady state tokamak demonstration fusion power plant, were a major radius R_0=9m, a minor radius a=2.25m, a plasma current I_P=14MA, a line averaged density $n_{e,lav}=8.8\cdot10^{19}\text{m}^{-3}$, a normalized plasma pressure β_N=2.2 and a magnetic field B=6.8T, aiming in a fusion power P_{fus}=1.6GW and a net electric power $P_{el,net}$=500MW [11].

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Two sets of profiles were used, one based on a flat density and the other based on a peaked density (see Fig. 1). These upper and lower boundary cases reflect the fact that there are some DEMO prediction uncertainties in defining the profiles (depending on the peaking of the density and as function of collisionality).

The profiles for DEMO1 were defined in close collaboration with the EFDA Task WP12-SYS02 (DEMO preliminary scenario analysis). Starting from the 0D PROCESS code results, the METIS code was used to develop time and space-dependent scenarios. It was decided to use the TRANSP transport code as reference and in combination with the ASTRA code (coupled to TORBEAM and FRTC) for calculating the CD behaviour of such profiles. It could be achieved that both delivered consistent results. The profiles represented in Fig. 1 are the prerequisites for the further calculations of the EC, LH and IC current drive efficiencies. For the work programme 2013 the analysis is on-going for the steady state DEMO – so called DEMO2 – in a similar way.

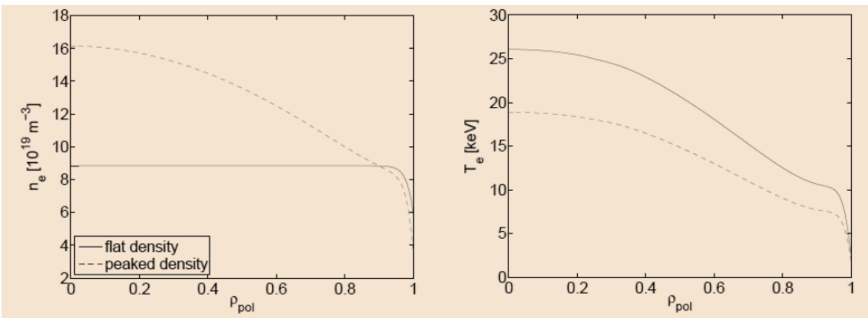

FIGURE 1. Density and temperature profiles as prerequisites for later described H&CD calculations, solid curve "flat density" case, dashed curve "peaked density" case [11].

The different possible functions of the H&CD systems while the plasma discharge are summarized in Fig. 2 and cover the start-up phase, ramp-up phase, burn phase as well as the current ramp-down phase and the inter-pulse wall conditioning. The analyses done so far have focused on CD assessments and profile control.

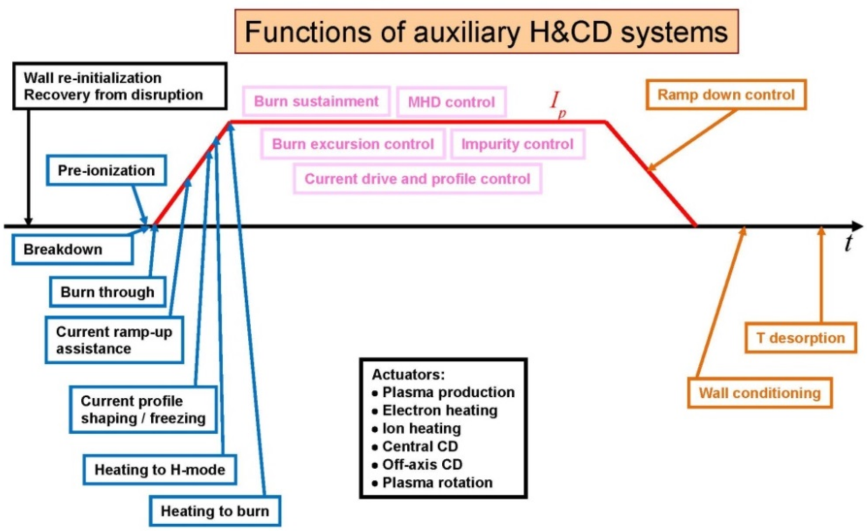

FIGURE 2. Functions of H&CD systems for DEMO [10].

GENERAL ASPECTS OF CURRENT DRIVE EFFICIENCY

For DEMO the figure of merit $\eta_{CD} \cdot \gamma_{CD}$ should be at least $0.25 \cdot 10^{20} \cdot A/(W \cdot m^2)$ [2] for CD systems, whereby:

- η_{CD} is the **wall-plug** or **overall efficiency** of the H&CD systems defined as product $\eta_{CD,conv} \cdot \eta_{CD,coupl}$.
  - $\eta_{CD,conv}$ is the *conversion efficiency* or *system efficiency*: i.e. the efficiency of the whole chain from the power supplies, generators, transmission lines and to the torus windows in EC case or antennas in LH and IC cases.
  - $\eta_{CD,coupl}$ is the *coupling efficiency*: for EC the coupling is nearly 100% except some stray radiation, for IC the coupled power is reduced by the edge losses (slow waves, sheath effects etc.) and can be assumed to be 80-90% [7] (further investigations necessary), for LH it is 85% respectively.
- γ_{CD} is the **current drive efficiency** defined as the local current drive efficiency:
  - $\gamma_{CD} = n_e(\rho) \cdot R_0 \cdot I_{CD} / P_{CD}(\rho)$ with $n_e(\rho)$ is the local density at $\rho = \rho_{dep}$, the position where the localized current of total value I_{CD} is driven with power $P_{CD}(\rho)$.

For the sake of completeness it should be mentioned that the global current drive efficiency is defined as:

- $<\gamma_{CD}> = n_{e,lav} \cdot R_0 \cdot I_{AUX} / P_{CD}$ for a given current profile $j_{AUX}(r)$.

The results obtained are summarized in Tab. 1. The γ_{CD} dependencies (Tabs. 2, 3) are explained in the text below.

TABLE 1: Comparison of the H&CD RF systems efficiencies for the *DEMO1 flat density case;* current drive, conversion and coupling efficiencies from [11] as far as available, otherwise according to actual values in present day tokamaks.

	LHCD	ECCD	ICCD
η Conversion: $\eta_{CD,conv}$	30-40%	40-50%	45-55%
η Coupling: $\eta_{CD,coupl}$	85%	100%	80-90%
Current drive efficiency γ_{CD} [10^{20}·A/(W·m²)]	0.30 (5GHz, Z_{eff}=2, $n_{\|}$=1.8)	0.34 (250GHz , on-axis, top lauch)	0.28 (72MHz, equatorial launch, Z_{eff}=2, n_ϕ= 25)
$\eta_{CD} \cdot \gamma_{CD}$	0.08-0.10	0.14-0.17	0.10-0.14
Power deposition	Peripheral	Flexible	On-axis
Remarks	SOL density and temperature affect wave characteristics	γ_{CD} depends on radius (lower when going off-axis)	SOL density profiles might affect antenna loading (limits the power available)

TABLE 2: CD efficiency for several EC frequencies and flat/peaked density cases for top launch. [11].

	ECCD γ_{CD} [10^{20}·A/(W·m²)]	
	Flat profile	Peaked profile
Power deposition on –axis	**0.34** (250GHz)	**0.33** (250GHz)
	0.41 (280GHz)	**0.36** (270GHz)

TABLE 3: Degradation of CD efficiency for IC with Z_{eff}, ($n_{e,0}=1\cdot10^{20}m^{-3}$, f=72MHz) for equatorial launch [11].

	ICCD γ_{CD} [10^{20}·A/(W·m²)] for flat density profile	
Z_{eff}	n_ϕ= 40	n_ϕ = 25
1.0	0.34	0.40
1.6	0.26	0.32
2.0	0.22	0.28

<u>**ICCD**</u>: In order to deduce the CD efficiency of Tab. 1, a frequency of 72 MHz, also suitable for plasma fuel heating, was assumed. The value given correspond to an 0 –π/4 –π/2 -3π/4 antenna phasing with higher CD obtained for lower toroidal mode numbers (Tab. 3). The CD value is also greatly affected by the assumed value for the effective charge Z_{eff} (Tab. 3). The IC current drive efficiency can be further improved by a factor of at least two compared to the values given (Tabs. 1, 3) by launching waves with higher frequencies from the top of the machine [6, 9]. As illustrated in Fig. 3, when the RF frequency is increased and while still using equatorial launch, the wave is absorbed by alpha particles at high harmonic cyclotron resonance, minimising the wave absorption by the electron and hence the CD efficiency. This *parasitic absorption* by alpha particles can be prevented by launching waves from the machine top [6]. It remains to be studied how to achieve efficient coupling for this case. Further considerations on the overall system efficiency, effect of the scrape-off layer (SOL) density and antenna technology for DEMO can be found in [7].

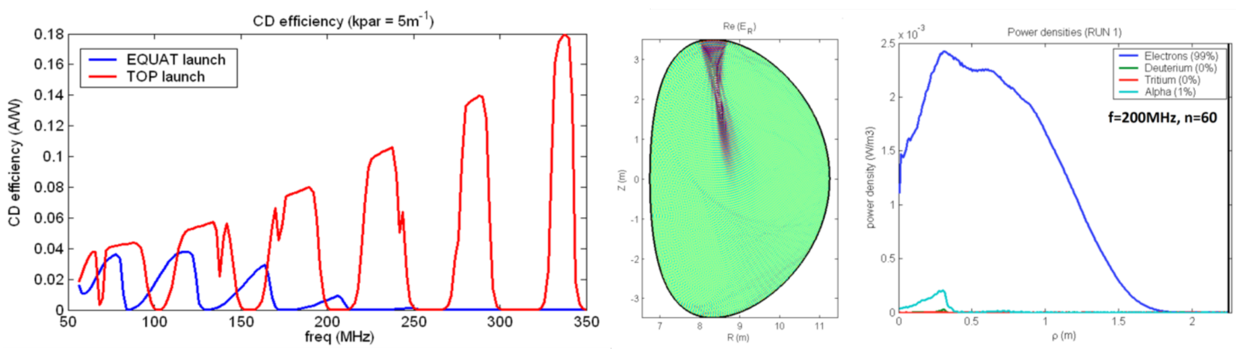

FIGURE 3. Evolution of the CD efficiency for equatorial launch with FWCD and top launch as function of the wave frequency (left). Electric field structure (middle) and power deposition profile for f=200MHz, top launch (right) [6].

<u>**ECCD**</u>: To deduce the CD efficiency of Tab. 1 a frequency of 250GHz was assumed. As shown in Tab. 2, the use of a frequency of the order of 270-280GHz would give the best CD values for DEMO1 if technically feasible. The selection of 250GHz was done under consideration of the technical maturity of the EC system and an extrapolation of state-of-the-art high power gyrotrons technology from ITER to DEMO. It can be seen that for the flat density profile a CD efficiency γ_{CD} of $0.34\cdot10^{20}\cdot A/(W\cdot m^2)$ can still be obtained. To prevent *parasitic absorption* the best case was found by injection of the EC wave from the machine top. By changing the poloidal and toroidal

angle of the EC beams (Fig. 4), and hence changing the power deposition the CD efficiency could be increased to about a factor of two compared to equatorial launch.

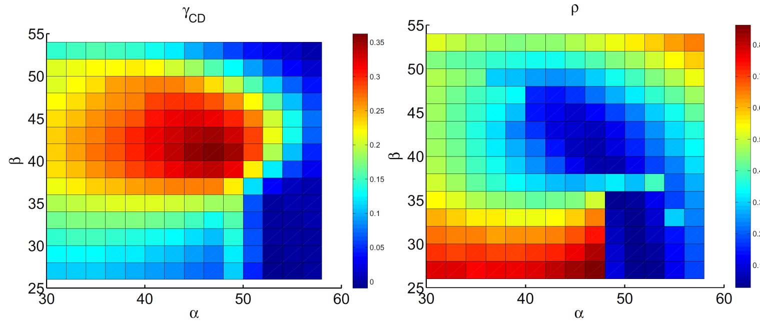

FIGURE 4: EC top launch CD efficiency and corresponding normalized radius ρ for different poloidal and toroidal injection angles α and β for the peaked density case at 270GHz [11].

LHCD: Two antenna spectra were analysed with the RAYstar and LHstar codes [4, 5] for $n_{\|,peak}$ of 1.5 and 1.8. The latter was found to be more suitable for a better penetration into the plasma, the first being largely inaccessible. Further work shows that *parametric instabilities* produced spectra broadening, with the chosen exponential decaying SOL, that do not seriously impair LHCD for DEMO plasmas. The power absorption was found in both density cases to be very peripheral as shown in Fig. 5 for 100MW at 5GHz from analyses with the ASTRA and FRTC codes.

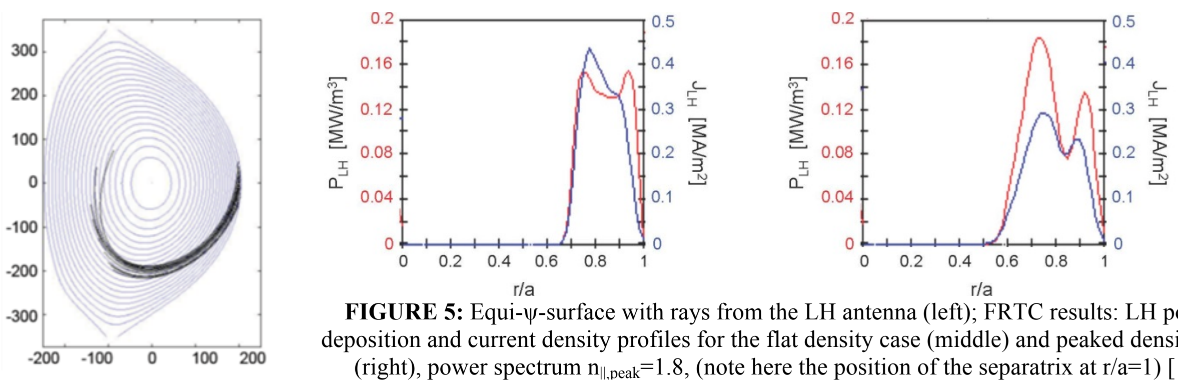

FIGURE 5: Equi-ψ-surface with rays from the LH antenna (left); FRTC results: LH power deposition and current density profiles for the flat density case (middle) and peaked density case (right), power spectrum $n_{\|,peak}$=1.8, (note here the position of the separatrix at r/a=1) [11].

SUMMARY & PREVIEW

The work carried out within the PPPT work programme 2012 shows the different aspects of RF systems for the opportunity to drive a considerable amount of plasma current. The figure of merit for $\eta_{CD}\cdot\gamma_{CD}$ of $0.25\cdot10^{20}\cdot$A/(W·m^2) is still a challenge for DEMO. The results nevertheless show a good progress. The intent for a DEMO1 is to work as pulsed device with less current drive power. The studies are on-going in 2013 for the steady-state DEMO2 with a reduced major radius of 8.5m and expected higher current drive efficiencies because of higher plasma temperatures.

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REFERENCES

1. H. Zohm et al., 'On the Physics Guidelines for a Tokamak DEMO', Nuclear Fusion 53, 073019 (2013).
2. J. Pamela et. al., 'Efficiency and availability driven R&D issues for DEMO', Fusion Engineering and Design 84 (2009).
3. G. Federici et. al., 'EU DEMO Design and R&D Studies', SOFE 2013.
4. A. Cardinali et. al., Assessment of the LH Wave for DEMO in Pulsed and Steady State Scenario, this conference.
5. S. Ceccuzzi et. al., LHCD for DEMO: Physics Assessment and Technology Maturity, to be published on Fusion Sci. Technol.
6. E. Lerche, D. V. Eester, A. Messian, Fast Wave Current Drive in DEMO, this conference.
7. M. Nightingale et. al., FWCD Technology Issues for DEMO, this conference.
8. E. Poli et. al., Electron-cyclotron-current-drive efficiency in DEMO plasmas, Nucl. Fusion 53 013011, 2013.
9. R. Koch et. al. High frequency fast wave current drive for DEMO, AIP Conf. Proc. 1406, 349 (2011).
10. B. Weyssow, et. al., Presentation, Meeting with Industry and Associations, EFDA PPPT WP2011, 10.-11. May 2011.
11. EFDA PPPT WP12-DAS-HCD Final Reports (source EFDA IDM Document Management System).