FWCD technology issues for DEMO

M. Nightingale, E. Wooldridge, and I. Monakhov

FWCD technology issues for DEMO

M. Nightingale, E. Wooldridge, and I. Monakhov

Citation: AIP Conference Proceedings **1580**, 386 (2014); doi: 10.1063/1.4864569
View online: http://dx.doi.org/10.1063/1.4864569
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1580?ver=pdfcov
Published by the AIP Publishing

FWCD Technology Issues for DEMO

M. Nightingale, E. Wooldridge, and I. Monakhov

Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK

Abstract. The technology implications of potential FWCD systems have been assessed at two frequencies of relevance to DEMO as part of a wider study of heating and current drive systems for the EFDA Power Plant Physics and Technology (PPP&T), based upon two reference DEMO designs. Using the results of Van Eester et al [1], systems studies carried out for a 62MHz mid-harmonic system mounted on a 23MA 5.74T 8.5m major radius DEMO suggested that antenna voltages close to 50kV, and the handling of the resultant sheath power loadings, are likely to be required if all of the 12.9MA non-bootstrap current drive is to be provided by FWCD. The "wall plug" electrical efficiency of the mid-harmonic option of $0.18 A/W.m^2$, potentially rising to $0.23 A/W.m^2$ with the future development of solid state generators, however, looks very attractive, and the coupling is less sensitive to plasma edge parameters than for existing antennas, due to the low $k_{//}$ of $2.8 m^{-1}$. The design could be based upon that presently under consideration for ITER, except for the replacement of insulating vacuum windows located relatively close to the plasma with all-metal designs [2]. A 352MHz high-harmonic option also looks technologically feasible, using a waveguide-based design and a port plug layout has been provided. This option might bring sheath effect and voltage hold-off benefits, but this is far from proven. In this case, systems studies were not feasible due to a lack of firm results from the physics studies. For both options: (a) the RF generators, power supplies and transmission line components required are either already available, or are under development for ITER, and (b) mechanical and material issues associated with the proposed FWCD antenna structures appear challenging, but will need solving on a wider basis across DEMO.

Keywords: DEMO, FWCD, ICRH
PACS: 52.55.Fa, 52.50.Qt , 52.55.Wq

INTRODUCTION

The technology issues associated with the provision of a port-based Fast Wave Current Drive (FWCD) system for DEMO have been assessed as part of PPP&T contract WP-11-DAS-HCD-IC-01. For the purposes of this study, two DEMOs were defined by Ward [3]: DEMO1 was an 18MA 7.45T pulsed device, designed to be a relatively straightforward extrapolation from ITER; DEMO2 a 23MA 5.74T representative steady state design. Information from recent physics studies was used to define a likely antenna specification and number of ports for a FWCD system for DEMO2, and a technology assessment was carried out for both DEMO options.

SYSTEM STUDIES

Input from Physics Modelling

Three basic options exist for a FWCD system: (a) sub-harmonic at a frequency below the lowest ion cyclotron resonance; (b) mid-harmonic at a frequency with a suitable gap in the ion damping; and (c) high-harmonic FWCD at a frequency above the highest 3^{rd} harmonic ion cyclotron resonance.

The methodology for establishing the conversion from total RF power to driven current is shown in Figure 1. As part of the same PPP&T study, Van Eester [1] provided the current drive efficiency for a mid-harmonic FWCD system capable of meeting DEMO2 requirements at a frequency of 62MHz. This suggested that the highest current drive efficiency should be achieved at toroidal wave number $k_{//}$ of order $1.5 m^{-1}$ with corresponding current drive efficiencies of order 0.06A/W. Van Eester's model included: the power absorbed by other species, including impurities; the effects of the real $k_{//}$ spectrum; both in terms of coupling and in the current drive efficiency calculation; and the correction for the current driven in the negative toroidal direction, but did not include the effects of power lost to competing modes at the edge. It was assumed for the present study that this latter loss largely comprises the power in the spectrum that lies below an $n_{//}$ of unity which van Eester showed to be of order 5-6%. A conservative value of 10% total loss at the edge was assumed for the study.

Radiofrequency Power in Plasmas
AIP Conf. Proc. 1580, 386-389 (2014); doi: 10.1063/1.4864569
2014 AIP Publishing LLC 978-0-7354-1210-1/$30.00

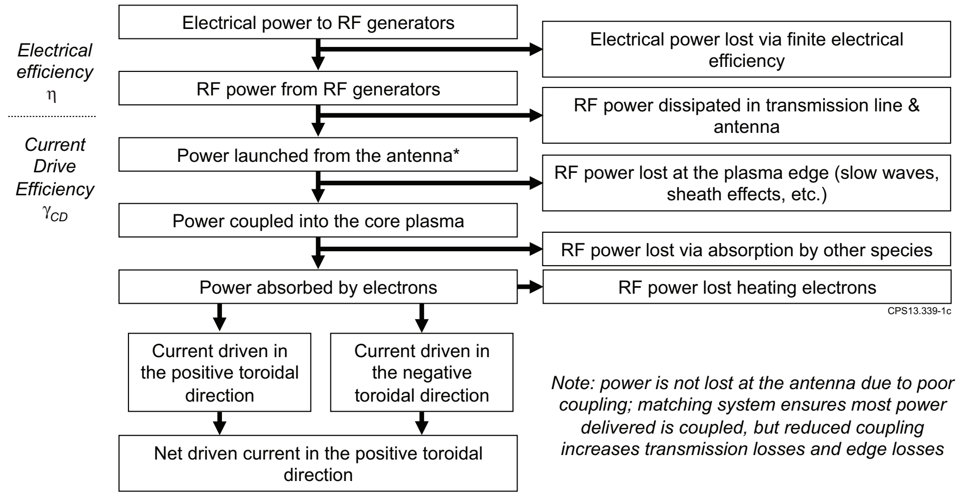

FIGURE 1. Methodology Used for Determining the Number of Ports and the Total ICRH Electrical Power

For the proposed DEMO port width of 2.236m (see below), the requirements to achieve $\pi/2$ phasing across the port plug and to achieve an inter-strap spacing of no less than 30cm meant that $k_{//}$ needed to lie between $2.8m^{-1}$ and $5.2m^{-1}$. Since Van Eester's studies showed the peak current drive efficiency was achieved at even lower $k_{//}$, the minimum value $2.8m^{-1}$ (corresponding to N_ϕ=32, $n_{//}$=2.2), was assumed for this study. The resultant current drive efficiency, including the correction for edge loses, was 0.048A/W (normalised current drive efficiency $\gamma_{CD} = R.n_e(10^{20}m^{-3}).I/P$ of $0.37A/W.m^2$). Van Eester indicated a somewhat lower value of 0.042A/W, but this assumed the ITER antenna geometry, which has a higher dominant $k_{//}$ (closer straps) and the full spectrum was considered. More recent work by Lerche [4] was for a DEMO machine of lower central T_e (29keV, rather than 50keV) which dropped the current drive efficiency to 0.032A/W at Z_{eff}=1.6 and $k_{//}$ of $2.8m^{-1}$. This modelling also showed that the drop in current drive efficiency due to the reduction in T_e was of order 1.5 for the $k_{//}$ values considered, and so this more recent work suggests a current drive efficiency of more than 0.05A/W at 50keV, $k_{//}$=$2.8m^{-1}$ and Z_{eff}=1.6. In a recent study, using the DEMO designs defined by Maisonnier et al [5], Hannan [6] predicted current drive efficiencies for a 28MA 6.9T 40keV DEMO of 0.035-0.04A/W at n_ϕ of order 30 and a Z_{eff} of 2.7. Using the temperature and Z_{eff} scaling noted by Lerche suggests that the Hannan results would also correspond to a current drive efficiency of more than 0.05A/W at 50keV and Z_{eff}=1.6. The 0.048A/W used in this present study is consistent, therefore, with more recent modelling, scaled to 50keV DEMO designs.

Assumptions

In order to establish the likely number of FWCD ports, the following assumptions were made:

1. *Total FWCD Power Requirement*: a plasma current of 23MA at a bootstrap fraction of 44% was specified for DEMO2. A FWCD system providing all of this current will need to drive 12.9MA, corresponding to 270MW of total coupled ion cyclotron power given the current drive efficiency of 0.048A/W discussed above.
2. *Port Size*: No DEMO port size has been agreed, and so this study assumed that to first order that the available ports will be the size of those on ITER, scaled with the machine outer radius. Allowing space for neutron shielding and cryostat between the port and surrounding TF and PF coils resulted in a 2.24m wide x 2.68m high FWCD port.
3. *Far SOL profile*: there is no adequate model for the DEMO SOL that can be used to predict the ICRH coupling. The best option for the present purposes was to take a pessimistic version of the ITER far-SOL plasma density profile (the sc2short17 edge discussed by Messiaen [7]), which led to a distance from the straps to the cut-off density of 11.6cm.
4. *RF voltage*: 35kV is proposed as a compromise between the 30kV routinely achieved on JET, and the 45kV assumed for ITER.

Results

A "figure of merit" *f* for current drive systems is the product ($\eta.\gamma_{CD}$) where η is the electrical efficiency (assumed for FWCD to comprise: 95% for the HV and auxiliary systems; 65% for the RF generators and 80% for the transmission line from the generator to the matching system). The above γ_{CD} value suggests that *f* for FWCD should be of order 0.18A/W.m^2, potentially rising to 0.23A/W.m^2 if the development of solid state technology could raise RF tube efficiencies toward 80%. It appears, therefore, that FWCD offers an attractive option in terms of overall wall plug efficiency, but note that Pamela et al [8] proposed that an *f* of 0.23 looks to be marginal with respect to recirculating power, and the figure derived here assumes a high T_e DEMO, which may not be realizable.

The number of FWCD ports has been estimated by extrapolation of coupling measured on JET. Using the approach described in Nightingale et al [9], values for the DEMO coupled power per port were obtained by scaling from the JET ITER-like antenna coupling of 1.48Ω/m measured at 42MHz at a $k_{//}$ of 6.7m^{-1} at an estimated distance from the antenna straps to the cut-off density position d_c of 8.3cm using

$$P_{strap} \approx \frac{V_{strap}^2}{2Z_c^2} R^{'} L_{strap} \propto \frac{V_{strap}^2}{2Z_c^2} L_{strap}\, \omega \exp\left(-1.5 k_{//} d_c\right)$$

where the factor of 1.5 was determined empirically. It was assumed here that the total strap height per column L_{strap} was 80% of the total port height. Assuming four strap columns per port, the resultant coupled power per port was 19.1MW (3MW/m^2). A total power of 270MW will therefore require 15 ports, which is well above a suitable target figure of one third of the total number of ports. As a result, the above analysis has been repeated varying: (a) the position of the fast wave cut-off; and (b) the operating RF voltage, as shown in Figure 2. The results show that the cut-off position dependence is relatively weak (due to the very low cut-off density value at the proposed $k_{//}$), but improvements in voltage hold-off would produce significant benefits, and improving voltage hold-off for ICRH antennas should be a long term aim.

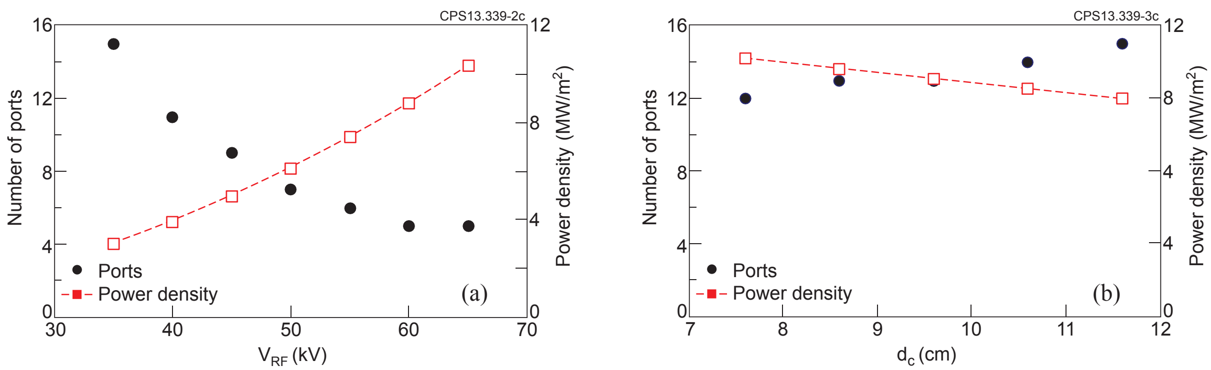

FIGURE 2. Variation in the Number of Required Ports with (a) Antenna Voltage and (b) Distance to the Cut-Off Density.

TECHNOLOGY ASSESSMENT

Given the current drive requirements discussed above, the technology required to satisfy these requirements have been assessed for both mid-harmonic (62MHz) and high-harmonic options, as shown in Table 1. A frequency of 352MHz was chosen for the high frequency system because of the availability of existing CW components.

TABLE 1. FWCD Technology Options

Frequency	Component	Available Technology	Present Status
62MHz	Generators	Tetrodes	2.5MW 3200s tube under development for ITER
	Transmission Systems	Co-Axial Lines	CW lines under development for ITER
	Launchers	Strap-Based Antennas	Under development for ITER; window issue [a]
352MHz	Generators	Klystrons	CW tubes exist
	Transmission Systems	Waveguides	CW waveguides exist
	Launchers	Waveguide-based Launcher	Novel concept [b]

[a]at 62MHz the key issue is the need to position a launcher window relatively close to the plasma in order to support the transmission line. The use of an all-metal support system based upon that of Moriyama [2] appears promising, as shown in Figure 3.

[b]at 352MHz the use of a waveguide-based launcher shown in Figure 4, using the folded waveguide concept [10], offers potential in terms of lack of window, reduced sheath voltages, but neutron streaming could be an issue.

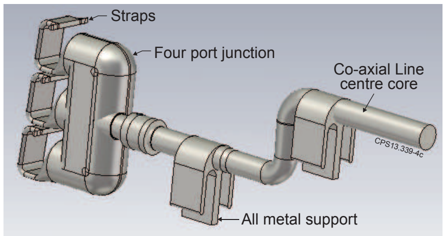

FIGURE 3. Proposed All-Metal Co-axial Antenna Option

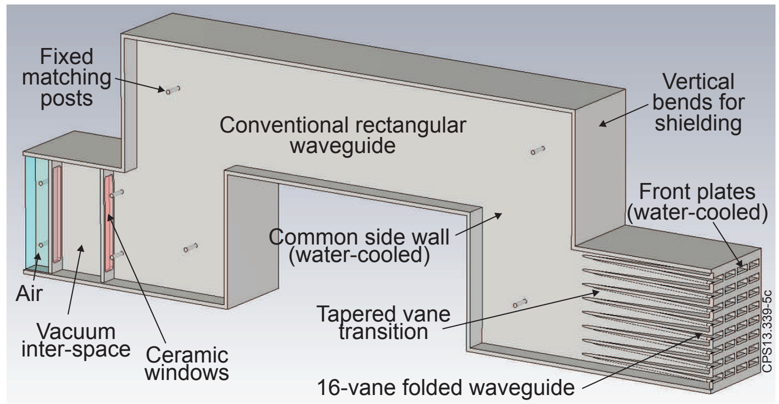

FIGURE 4. Proposed High Frequency Waveguide-Based ICRH Launcher

CONCLUSIONS

An assessment of the technology implications for FWCD systems proposed for DEMO has shown: (a) A mid-harmonic FWCD system, based upon the principles underlying the proposed ITER antenna, appears feasible from the technology perspective, providing one relatively novel antenna structure change can be developed to avoid excessive disruption forces; (b) this mid-harmonic option is unlikely to achieve the power density required for DEMO without further developments to increase voltage hold-off in typical ICRH antennas; (c) the “wall plug” electrical efficiency of the mid-harmonic option, however, looks attractive; (d) A high harmonic option also looks feasible, using a system based upon waveguides, might bring sheath effect and voltage hold-off benefits, but this is far from proven; and (e) the RF generators, power supplies and transmission line components required for the two options are either already commercially available or are under development for ITER.

ACKNOWLEDGMENTS

This work was funded by the RCUK Energy Programme and the European Communities under the contract of Association between EURATOM and CCFE and was carried out within the framework of the European Fusion Development Agreement EFDA PPPT Work Programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

1. D. Van Eester, “Report on the Potential of ICRH in DEMO” (2012)
2. S. Moriyama et al, *Fusion Engineering and Design*, **39–40** 135–142 (1998)
3. D. Ward, “Proposals for Initial PPPT H&CD Assessments” (2011)
4. E. Lerche, this conference (2013)A. Messiaen et al, Nucl. Fusion **50** (2010) 025026
5. D. Maissonier et al, *Fus. Eng. and Design* **81** 1123 (2006)
6. A. Hannan, T. Hellsten and T. Johnson, *Nucl. Fusion* **53** 043005 (2013)
7. A. Messiaen et al, *Nucl. Fusion* **50** 025026 (2010)
8. J. Pamela et al, *Fus. Eng and Design* **84** 194 (2009)
9. M. P S. Nightingale et al., *Radio Frequency Power in Plasmas*, Proc. 18th Topical Conference p. 213 (2009)
10. T. L. Owens, IEEE Trans. Plasma Science **PS-14** 934 (1986)