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Technological and Physics Assessments on Heating and Current Drive Systems for DEMO

T. Franke^{1,2}, E. Barbato³, G. Bosia⁴, A. Cardinali³, S. Ceccuzzi³, R. Cesario³,
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E. Poli², L. Porte⁹, G.L. Ravera³, E. Surrey⁸, G. Tardini², M.Q. Tran⁹,
C. Tsironis^{10,11}, A.A. Tuccillo³, R. Wenninger¹, H. Zohm², EFDA PPP&T team¹
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

¹*EFDA Close Support Unit, Boltzmannstr. 2, D-85748 Garching, Germany*

²*Max Planck Institute for Plasma Physics, Boltzmannstr. 2, D-85748 Garching, Germany*

³*Unità Tecnica Fusione ENEA, C. R. Frascati, via E. Fermi 45, 00044 Frascati (Roma), Italy*

⁴*Department of Physics, University of Turin, Via P. Giuria 1, 10125 Turin (Italy)*

⁵*Laboratory for Plasma Physics, LPP-ERM/KMS, TEC & Belgian EUROfusion Consortium partner,
Brussels, Belgium*

⁶*Karlsruhe Institute of Technology (KIT), Association EURATOM-KIT,
Kaiserstrasse 12, 76131 Karlsruhe, Germany*

⁷*CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

⁸*CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK*

⁹*Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne (EPFL),
Station 13, CH-1015, Lausanne, Switzerland*

¹⁰*Department of Physics, Aristotle University of Thessaloniki, Greece*

¹¹*School of Electrical and Computer Engineering, National Technical University of Athens, Greece*

* See annex of F. Romanelli et al, "Overview of JET Results",
(24th IAEA Fusion Energy Conference, San Diego, USA (2012)).

ABSTRACT

The physics requirements of the heating and current (H&CD) systems in a Demonstration Fusion Power Plant (DEMO) are often beyond the actual level of design maturity and technology readiness required. The recent EU fusion roadmap advocates a pragmatic approach and favours, for the initial design integration studies, systems to be as much as possible, extrapolated from the ITER experience. To reach the goal of demonstrating the production of electricity in DEMO with a closed fuel cycle by 2050, one must ensure reliability, availability, maintainability, inspectability (RAMI) as well as performance, efficiency and optimized design for the H&CD systems.

In the recent Power Plant Physics & Technology (PPP&T) Work Programme a number of H&CD studies were performed. The four H&CD systems Neutral Beam (NB) Injection, Electron Cyclotron (EC), Ion Cyclotron (IC) and Lower Hybrid (LH) were considered. First, a physics optimisation study was made assuming all technologies are available and identifying which parameters are needed to optimize performance for given plasma parameters. Separately, the (i) technological maturity was considered (e.g. 240GHz gyrotrons for EC) and (ii) technologies were adapted (e.g. multi-stage depressed collector for EC) or (iii) novel solutions (e.g. photo-neutralization for NB or new antennae concepts for IC) were studied to overcome the limitations of the present H&CD systems with respect to DEMO requirements. Further constraints imposed by remote maintenance or breeding blanket interactions were considered.

FOREWORD

In this paper the extensive work of the various H&CD groups during the last years will be highlighted and some of the important new findings summarized. More details can be found in the reference list [1]-[19]. All final reports of the work-programmes 2011–2013 are available in the EFDA IDM database for the EUROfusion Consortium Members and Auditors [20].

1. INTRODUCTION

To prepare the DEMO conceptual design activity (CDA) phase initiated in 2014, work was carried out in a pre-conceptual design phase during 2011–2013 in view of the engineering design activity (EDA) phase of DEMO starting around 2020 [1] and chasing the Fusion Roadmap [2] of operation the prototype fusion power plant in 2050. The work on H&CD systems was based on two regimes of plasma operations which are (i) a *pulsed machine* with either no (or marginal) current drive (CD) power or with reasonable but limited bulk CD power in case of an *extended long pulse machine* and (ii) a *full steady-state machine* with significant H&CD power. The work described here concentrates on the case of a *pulsed machine* [2]. Full steady state operation requires challenging, but not unrealistic efficient technologies [3] compared to current state-of-the-art of H&CD systems regarding wall-plug and CD efficiencies. The recirculating power is limited such that the net electric power to the grid is $\sim 500\text{MW}_e$ and the pulse flat top length is optimized to achieve a high duty cycle [4].

2. POWER PLANT DESCRIPTION

2.1. DEMO PARAMETERS

The basic tokamak parameters of the current pulsed DEMO reference design are given in Table 1 and derived from PROCESS. This 0D-code is taking into account the main DEMO fusion power plant systems (e.g. pumping, fuelling, magnetic coils, balance of plant and site) to optimize the tokamak and its performance and costs.

To improve the DEMO tokamak, in terms of plasma control (vertical stability), disruption forces and a number of other issues, an aspect-ratio trade-off study is under way [5]. The study includes the choice of a different EC frequency for each chosen magnetic field strength and the NB layout (e.g. tangential angle). The number of the TF coils is varied to see influences to the magnetic ripple and therefore the ion losses.

2.2. H&CD POWER REQUIREMENTS

The H&CD power is needed for all three plasma pulse phases, namely (i) plasma start-up, (ii) plasma flat-top and (iii) pulse termination and/or off-normal event shut-down. During the *first phase* the H&CD power is used for the a) plasma breakdown, b) burn-through, c) assisted current ramp-up and d) heating to H-mode, while during the *second phase* it is used for e) burn control, f) MHD control, g) impurity control and depending on the regime more or less h) current drive. During the *third phase* it serves for the i) assisted ramp-down. No H&CD functionality is planned for dwell time between pulses, but if so, H&CD methods could be used for T-desorption, wall conditioning, etc. Depending on further physics findings, the optimal H&CD drive mix can be determined, meanwhile for the present DEMO the assumptions are to use (i) EC for assisted breakdown, electron heating, CD and MHD control, (ii) NB for heating and CD, (iii) IC for mainly bulk ion heating, impurity control and it could potentially contribute to CD. Studies done so far suggest LH is not considered for the pulsed machine but might play a significant role for an efficient far off-axis CD in the steady-state regime.

2.2.1. Auxiliary Heating Power

The thermal power balance in a tokamak is given by $P_{fusion} + P_{aux} = P_{loss} + P_{neutron}$ with $P_{fusion} = P_{neutron} + P_{\alpha}$ and $P_{loss} = P_{rad} + P_{sep}$, where the radiation losses inside the separatrix P_{rad} include line radiation, Bremsstrahlung and synchrotron radiation. The power crossing the separatrix P_{sep} determines the thermal loads on the divertor. For the DEMO reference case it was assumed $P_{sep} \approx 1.3 \cdot P_{L-H}$, (present studies use $P_{sep} \approx P_{L-H}$) where P_{L-H} is the H-mode threshold. The H&CD power of 50MW had initially been fixed in the PROCESS code runs, strongly influenced by ITER studies and requires re-assessment. In fact first rough METIS calculations indicate the required power for the ramp-up to be at least 50MW and possibly even beyond 100MW, depending on the assumptions and tokamak start-up time, whereby a longer ramp-up time requires lower H&CD power.

2.2.2. Current Drive Power

The CD power needed depends on several plasma parameters and systems properties, but also on geometrical factors: in case of NB the tangential radii of the beams and in case of EC the launching angles and positions of power deposition of the waves, the latter are also the case for IC. Several studies were made to optimize the CD efficiencies assuming either EC, NB or IC [6]-[9]. Not surprisingly, the CD efficiency depends on the plasma profiles. The profiles were calculated beginning from 0D-code PROCESS to optimize the tokamak. The outcome of those studies was then fed into the transport codes ASTRA/TRANSP yielding the 1D kinetic plasma profiles. In all cases of the reference design (with or w/o CD) and the aspect ratio scans, the bootstrap current has been kept at a realistic level of about 35%.

The plasma burn time is given by $t_{burn} \sim (|\Phi_{tot}| - \Phi_{start}) / (I_p \cdot R_p \cdot \{1 - f_{non-inductive}\})$. Φ_{tot} is the total magnetic flux of the central solenoid coil, Φ_{start} is the flux required for the start-up of the plasma and R_p is the plasma resistance. Assuming Φ_{tot} , Φ_{start} and R_p constant one can calculate the plasma pulse length with versus w/o CD. Applying 50MW of auxiliary power for CD fraction $f_{aux,CD}$ the total plasma current I_p driven from $f_{aux,CD}$ is about 10% (depending on the CD efficiency). The non-inductive fraction is $f_{non-inductive} = f_{aux,CD} + f_{BS}$, where f_{BS} stands for the bootstrap-fraction. The calculated pulse length with CD slightly increases compared to the pure inductively driven pulse by about 25min to $\sim 2.7h$, cf. Figure 1.

2.2.3. EC assisted breakdown and MHD control

The results of first simulations for the pulse start show a modest power for the plasma breakdown and burn-through of about 6–12MW. Also the question of magnetohydrodynamics (MHD) control was considered during the assessments. The stabilisation of the Neo-classical Tearing Mode (NTM) is achieved by EC control. In a first scan for different poloidal and toroidal launch angles at the $q = 2$ and $q = 3/2$ surfaces the injected EC wave power was set to be 4.5–7MW and it could be shown that with this EC power the stabilisation criterion could be met over a wide radial range [20].

3. H&CD SYSTEMS

The modularity of the systems very much influences their total availability and possible up-time. Whereas in case of EC the gyrotrons have about 1MW (@240GHz) per unit and in case of failure of one or more units could remain operational and guarantee an intrinsic high overall EC system reliability. The NB power of a single injector is rather high (~ 20 -25MW @1MeV). It is therefore foreseen to use modular NB sources inside the injector to increase the NB system overall availability in case of a fault in one source.

The physics studies for the different H&CD systems were made assuming two types of kinetic profiles a) flat and b) peaked density case. They were selected to represent the boundaries in which a later profile is expected. The related peak temperatures are varying between 19keV and 26keV

and the core density varies between $9 \cdot 10^{19} m^{-3}$ and $16 \cdot 10^{19} m^{-3}$. This has a major influence on the choice of technology and the injection point as can be seen below, cf. also [6][14].

3.1. NEGATIVE NEUTRAL BEAM INJECTION (NNBI) SYSTEM

The NNBI system of DEMO shall benefit as much as possible from ITER. The specifications require a NB system with 1MeV and a total power of > 50 MW. The following DEMO relevant work has been carried out:

- Efficiency studies show that the CD efficiency is reduced by $< 5\%$ (on axis, peaked) to 10% (overall average) for the case of beam energy of 1MeV compared to 1.5MeV, simulated by PENCIL [10] code for different tangential radii and elevations, combined with shinethrough studies. The studies also show that far off-axis CD increases the NB CD efficiency, cf. Figure 2.
- Investigating Cs-reduced sources and non caesiated / alternative sources, e.g. matrix sources [11], negative ion production on boron-doped-diamond (BDD) [12], modelling of Cs chemistry and the plasma source.
- Improving RF-coupling and testing of recently commissioned solid state RF-generator for NB sources.
- Increasing the wall plug efficiency, presently $\sim 24\%$, by implementing a negative (and positive) ion energy recovery system to 29% (34% respectively) [13] was studied and with small scale mock up tested.
- Shielding and integration studies running MCNP code were done to determine whether the TF coils would be adequately protected around the NB port.
- Reducing the neutralisation losses by simulation to arrive at an optimized design of the beam neutralizer.
- Demonstrating the feasibility of photo-neutralization [15], the high finesse cavity (including stability and erosion of mirrors) and the CW high power lasers was examined, see Figure 3.
- High voltage breakdown behaviour was improved by modelling effects of depositions on electrodes and HV-bushings made of stainless steel.

3.2. EC SYSTEM

The selection of the operating frequency for EC is fundamental for development of the gyrotrons, transmission lines and launcher system. The optimum operating frequency for heating is given by the fundamental electron resonance frequency $f_{c,e} = \frac{\omega_{c,e}}{2\pi} = \frac{1}{2\pi} \frac{eB}{m_e} = 28GHz \cdot B[T]$. For the DEMO reference design, shown in Table 1, it results in heating frequency of about 190GHz (@6.8T). To find the optimum EC current drive (ECCD) frequency simulations were carried out in [6]. Different injection points (equatorial and top launch) and injection angles have been assumed. The optimum ECCD frequency has been found to be 280GHz using top launch. A reduction in frequency to relax the R&D efforts, taking into consideration e.g. the required magnetic field of the gyrotron superconducting (SC) magnet and the operation at very high order modes, leading

to a good compromise, where the frequency might be $\sim 240\text{GHz}$ with tolerable drawbacks ($\sim 15\text{--}20\%$) in CD efficiency.

Considering a future-multipurpose multi-frequency gyrotron, the following operating frequencies were identified: 136GHz (cf. W7X 140GHz), 170GHz (ITER), 204GHz , 238GHz (envisaged for CD for the present DEMO reference design) and eventually possible 272GHz . A frequency of 272GHz requires a very high magnetic field of the SC magnet of about 12T , whereas for 238GHz it is only 10T . The assumed output power per unit for 238GHz will be above 1MW , whereas for 272GHz it will be below 1MW .

Future gyrotron R&D has to concentrate on a sufficient output power level at operating frequencies above 200GHz , plug-in efficiencies above 60% , multi-purpose operation, frequency step-tunability, long life-time operation at CW operation and very high repetition rates. Gyrotron technologies developed for ITER are good starting point for DEMO. Nevertheless to achieve DEMO targets, key components like the electron emission and electron optical system has to be improved. Additionally broadband window technologies, e.g. chemical vapour deposition diamond (CVD) Brewster-angle windows [17] and multi-stage depressed collectors will have to be developed.

As part of the launcher studies different configurations on the remote steering (avoiding movable parts and mirrors due to high neutron and radiation fluxes) and their focussing capabilities of the EC millimetre wave were assessed for equatorial launchers and are being pursued for the upper port launcher. Integration studies showed that some space in the DEMO upper port is available but tight mainly due to the necessary integration of the blanket cooling pipes [18].

3.3. IC SYSTEM

In contrast to the very high EC frequency in the GHz range, the wave frequencies of a few tens of MHz are typically used for IC heating. The resonant frequencies for the central IC heating can be determined from $f_{c,i} = 15.2\text{MHz} \cdot (N \cdot Z/A) \cdot B[\text{T}]$, where N is the heating harmonics number, and Z/A is the charge-to-mass ratio of the resonant ions. For a DEMO operating at 6.8T , IC heating of tritium ions at the second harmonics requires the wave frequency of $\sim 70\text{MHz}$.

To optimize the CD efficiency, various design options were considered. The optimal frequency is in the $100\text{--}350\text{MHz}$ range for top launch with high harmonics fast wave CD and is $25\text{--}100\text{MHz}$ for fast wave CD (FWCD) for equatorial launch. These work results refer to an ITER-like antenna implemented in a port [8][9].

Recently the concept of a distributed antenna [19] for the WP2014-2020 was taken as a very promising design choice for DEMO, see Figure 4, having several advantages:

- Easy remote handling of the passive antenna structure as integrated part of the blanket segments.
- No extra cooling required, shared blanket cooling.
- Significantly reduced sheath-effects, sputtering and arcing or similar problems by reduced power density and voltage.
- Positioning of the antenna in the upper region avoids space occupations of ports with positive

impact on the Tritium Breeding Ratio (TBR). Such a wave launcher location also results in higher FWCD efficiency [9].

The conceptual design of the distributed antenna is in progress, further simulations and small scale testing are planned in the coming years to underpin the IC antenna strategy. An important aspect will be the proper material-selection and cooling of the plasma-facing front part of the antenna.

3.4. LH SYSTEM

Comprehensive work was done for the further investigation on the LH systems, in particular on (i) LH physics using ASTRA and FRTC codes, (ii) detailed work on main transmission lines and components to optimize converters, mode filters and bends, (iii) on CVD RF windows, on (iv) LH launchers, and (v) on RAMI. For the high power and long pulse (or CW) DEMO operation a slotted waveguide antenna (SWA) instead of presently used antenna types as Grill-, Multijunction- or PAM-antennas was proposed. The integration and first low power tests of a SWA LH launcher at 5GHz will be performed on the COMPASS tokamak in Prague.

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REFERENCES

- [1]. Tran M. Q. this conference (I4.3)
- [2]. Romanelli F. et al. EFDA Fusion roadmap
- [3]. Zohm H. et al. 2013 Nuclear Fusion **53** 073019
- [4]. Zohm H. Fusion Science and Technology **58** (2010), 613-624
- [5]. Wenninger R. et al. submitted IAEA (2014)
- [6]. Poli E. et al. 2013 Nuclear Fusion **53** 013011
- [7]. Surrey E. et al. Fusion Engineering and Design **87** (2012) 373-383
- [8]. Koch R. et al. AIP Conference Proceedings **1406** (2011) 349-352
- [9]. Lerche E. et al. AIP Conference Proceedings **1580** (2014) 338-341
- [10]. Challis C.D. et al. Nuclear Fusion **29** (1998) 563-570
- [11]. Lishev St. et al. Review of Scientific Instruments (2012) **83**, 02A702 (1-5)
- [12]. Kumar P. et al. Journal of Applied Physics **44** (2011) 372002 (4pp)
- [13]. Mc Adams R. Review of Scientific Instruments **85**, 02B319 (2014)
- [14]. Jenkins I. et al. 25th SOFE Conference, 2013
- [15]. Simonin A. AIP Conference Proceedings **1390**, (2011) 494-504
- [16]. Simonin A. accepted, 4th International Symposium NIBS, (2014)
- [17]. Gantenbein G. IEEE Transactions on Electron Devices **61** (2014) 1806-1811

- [18]. Bachmann C. this conference (P1.124)
 [19]. Bosia G. AIP Conference Proceedings **1406**, (2011) 133-136
 [20]. Final reports DAS-HCD-WP2013 EFDA_D_2M7L5P

Plasma Fusion Power (P_{fusion})	1572MW
Thermal Power	1972MW
Radiation Losses (P_{rad})	186MW
$P_{\text{L-H}}$	136MW
P_{sep}	180MW
P_{sep}/R	20MW/m
Thermal Efficiency	45%
Electricity Output	500MW
Major Radius	9.0m
Minor Radius	2.25m
Aspect Ratio	4
Toroidal Field (TF) Strength	6.8T
Number of TF coils	16
Neutral Beam Energy	1MeV
Z_{eff}	1.98
Auxiliary Heating Power (P_{aux})	50MW
Pulse Length	~ 2.3h

Table 1. Summary of a DEMO PROCESS code results [3].

<i>The X stands for the envisaged options under assessment</i>	Gyrotron Window	Torus Window
Brewster Angle Window	X	X
Double Disc Window	X	X
Grooved Diamond Disk Window	X	
Ring Resonator Based Window	X	

Table 2. Broadband Window Technologies for DEMO.

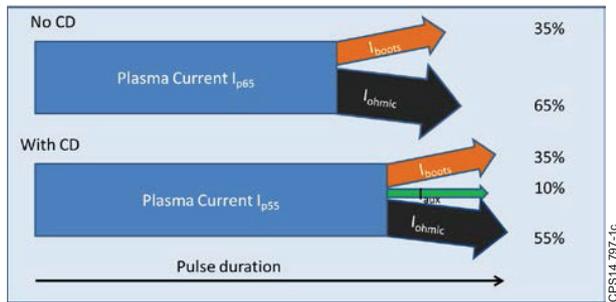


Figure 1. Diagram of the pulse duration and plasma current with / without CD.

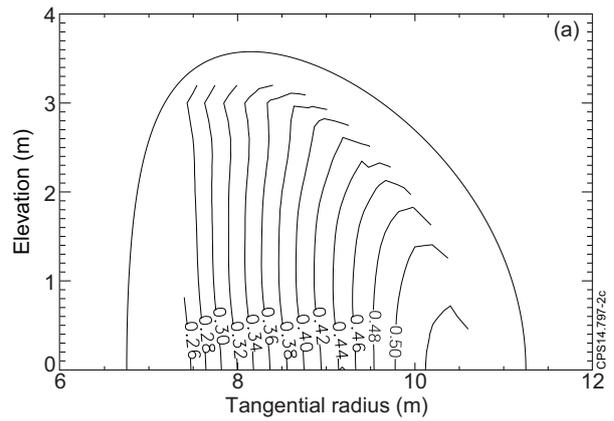


Figure 2. NBCD efficiency (in units 10^{20} A/W/m^2), plots for flat density scenario and beam energy $E = 1.0 \text{ MeV}$ [14].

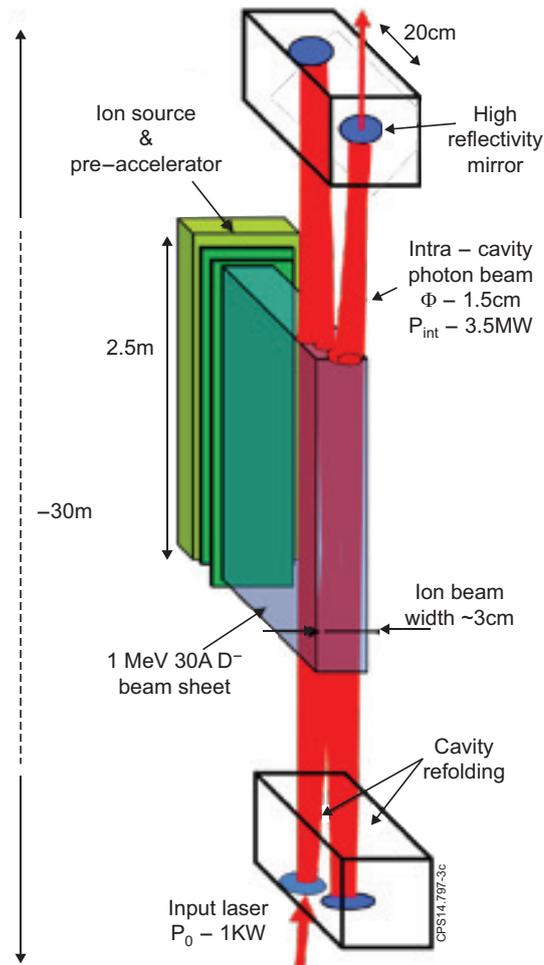


Figure 3. Schematic of the beam neutralization by a re-folded Fabry-Pérot cavity [16].



Figure 4. One sector of DEMO with an in-blanket IC antenna.

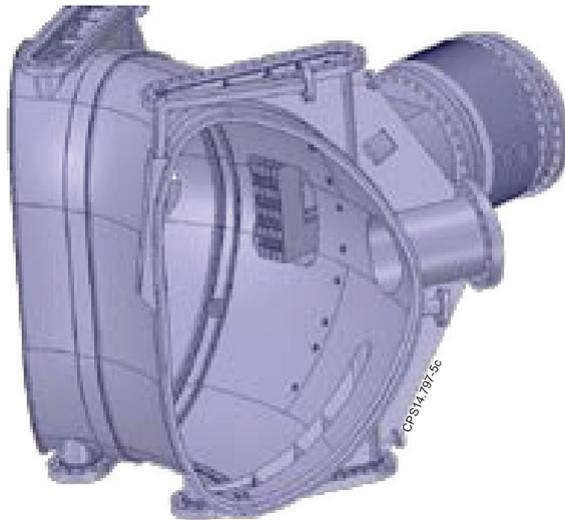


Figure 5. Narrow Side SWA port integration in COMPASS.

