

## EU DEMO Heating and Current Drive: Physics and Technology

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### Abstract

Within the European Fusion Roadmap the realization of a demonstration power plant, DEMO, which will produce substantial electrical power injected to electrical grids, is one main important element. In the frame of the Power Plant Physics and Technology (PPPT) programme, the EUROfusion Consortium is conducting detailed studies of DEMO, which, besides producing electricity, shall also be self-sufficient in Tritium production and meet the requirements on safety and environmental considerations. Presently (2016) two variants are studied: a long-pulse version (EU-DEMO1 2015) with pulse of >2 hours and a second variant, DEMO2, where the plasma is steady state and therefore which incorporates larger current drive power and larger bootstrap fraction. The physics requirements regarding heating and current drive for both DEMO1 and DEMO2, during the various phases of the plasma scenarios, will be addressed in the paper. The R&D programme on heating and current drive (HCD), launched in 2014, covers three heating methods (electron cyclotron wave, ion cyclotron wave and neutral beam injection) with the goal to gather the technical data and to develop more advanced concept, which in conjunction with the physics requirements, will allow the choice of heating mix for DEMO. From a strategic point of view, this selection will be performed towards the end of the conceptual design phase (around 2024).

### I. Introduction

Since 2014, the European fusion roadmap [1] has been the guiding document for the joint activities within the frame of the Consortium of research laboratories named EUROfusion. The roadmap foresees the demonstration of electricity production by 2050. In its implementation by EUROfusion, pre-conceptual design activities are presently performed under the programme "Power Plant Physics

and Technology" (PPPT). Detailed studies covering both physics and technology aspects of a DEMOnstration plant (DEMO) are being performed. DEMO is a tokamak reactor capable of delivering substantial amount of net electricity to the grid and satisfying the requirements of a fusion power plant such as Tritium self sufficiency, reliability and availability, safety aspects, remote maintenance, use of reduced activation material. In the design of DEMO, the heating and current drive (HCD) system will be a key element. The functions will depend on the scenarios, but will cover all phases of the operation of DEMO, from gas breakdown, plasma current ramp-up, burn phase and plasma ramp-down. The HCD systems under consideration by EUROfusion encompass electron cyclotron wave (ECW), ion cyclotron wave (ICW) and neutral beam injection (NBI). This paper will give an overview of the physics requirements for the HCD systems (Section II). A more detailed description of the ECW, ICW and NBI systems will follow in the Section III, IV and V.

## II. Physics Requirements

In the EU programme, two variants of DEMO are being investigated to account for the uncertainties in extrapolation of the present physics and technology. DEMO1 is a long pulse (>2 hours) tokamak based on conservative physics assumptions, while the plasma in DEMO2 is steady state with more aggressive physics assumptions. Table I gives the main parameters of DEMO1 and DEMO2 based on the output of the system codes PROCESS [2].

A few points can be noted from TABLE I and from the use of a system code. For DEMO1, the assumed fraction of  $I_{CD}/I_p$  is about 10 %. Therefore, besides some specific functions where CD is important such as NTM control, the non-inductive current is not important for maintaining  $I_p$  during the 2 hours pulse. In PROCESS, detailed physics functions for HCD during the flat-top phase and, more importantly, during the other phases of the plasma scenarios are not considered. As an example, power requirement during the current ramp-up and ramp-down of the current and the access to the H mode is not included in the power required during the flat-top phase as given in Table I ( $P_{FT} = 50$  MW for DEMO1). These issues were assessed using more specialized codes as described below.

The DEMO physics integration has therefore conducted more detailed simulations of the heating and current drive power requirements during the different phases of the plasmas. For the breakdown phases, as for ITER, a moderate power of ECW is required. For example, for DEMO1, a reference power of in the range of 6-10 MW at 170 GHz is required. The current drive analysis in flat-top is based on time dependent 1-d transport codes (ASTRA and TRANSP) that fix the magnetic equilibrium, but evolve the kinetic profiles together with the current profile. Here, the shape of the kinetic profiles is based on our present understanding of H-mode physics, i.e. a pedestal consistent with linear peeling ballooning stability in combination with a stiff temperature gradient model and, if the safety factor  $q(0)$  falls below unity, a sawtooth model. Density profiles are assumed to be peaked in accordance with theoretical understanding which allows the line averaged density to exceed the Greenwald density while the edge pedestal density is kept below the empirical Greenwald limit [3]. The transport coefficients are then adapted such that the integrals over the profiles match the 0-d values of  $\beta$  and  $n_{e,linav}$  as well as the H-factor to design these operational points. Seed impurities required to reduce the power flux across the separatrix in order to protect the divertor are included as well [4].

As pointed out above, with DEMO1 being mainly an inductive tokamak, current drive will contribute only weakly to the pulse duration (about 10 %) and the required power is determined by ramp-up and heat-to-burn, burn control, control of MHD stability and ramp-down. For the ramp-up phase, simulations using METIS Code show that a total of about 100-150 MW are proposed to achieve a robust access to H mode [5]. More detailed studies are on-going to optimize the power during ramp-up and ramp-down phases. Neoclassical Tearing Modes (NTMs) are assumed to be the main stability issue in DEMO1, with the power requirements similar or below those of ITER, i.e. in the range of 10 MW. While 50 MW seem to be sufficient for burn control, first modelling studies of the recovery of impurity events indicates a temporary higher requirement [6]. Combining this with the heat-to-burn

studies mentioned above, for DEMO1, about 150 MW installed power are considered, albeit not needed simultaneously for most of the discharge.

	DEMO1	DEMO2
Major radius	9.1 m	7.5 m
Aspect ratio A	3.1	2.6
Elongation $\kappa_{95}$	1.59	1.8
Triangularity $\delta_{95}$	0.33	0.33
Plasma duration	2 hours	Steady state
Toroidal field at plasma center, $B_T$	5.7 T	5.6 T
Number of TF coils	18	18
Central electron density	$1.01 \times 10^{20} \text{ m}^{-3}$	$1.22 \times 10^{20} \text{ m}^{-3}$
Greenwald density fraction	1.2	1.2
Central electron temperature $T_{e0}$	27.4 keV	34.6 keV
Average electron temperature $\langle T_e \rangle$	13 keV	18.2 keV
Energy confinement time	4.2 s	4 s
Central ion temperature $T_{i0}$	27.36 keV	34.66 keV
Average ion temperature $\langle T_{i0} \rangle$	12 keV	18.07 keV
Plasma current $I_p$	19.6 MA	21.6 MA
Inductively driven current	10.8 MA	0 A
Bootstrap current $I_{BS}$	6.9 MA	13.2 MA
Fraction of $I_{BS}/I_p$	35%	61%
Non inductive current $I_{CD}$	1.9 MA	8.4 MA
$I_{CD}/I_p$	9.60%	38.80%
Additional H&CD power during flat-top phase $P_{FT}$	50 MW	133 MW
L-H transition power threshold using ITPA scaling	133 MW	128 MW
Fusion power	$2037 \text{ MW}_{th}$	$3255 \text{ MW}_{th}$
Net electric power	$500 \text{ MW}_e$	$953 \text{ MW}_e$
Recirculating power used in PROCESS	$413 \text{ MW}_e$	$706 \text{ MW}_e$

TABLE I Main physics parameters of DEMO1 and DEMO2 from the system code PROCESS [Ref. 2]

For DEMO2, CD is an essential ingredient, and the aim is to arrive at an optimum design, with 120 MW as target for the CD function. At present, this goal has only been achieved using NBCD due to the relatively high  $Z_{\text{eff}}$  needed to protect the divertor, which deteriorates the ECCD and ICCD efficiencies. A design issue for NBCD is the access through the TF coils, which limits the higher tangential injection angle needed for off-axis NBCD. In principle, both NBCD and ECCD can be used alone to synthesize a given current profile [7], and for ECCD, it is assumed that it should also be used in DEMO2 for NTM stabilization with the power requirements similar to those given above for DEMO1. These tasks define the points of the ECCD launchers, which have to be integrated in the design of the in-vessel components. ICCD schemes are more explorative at the moment, and proper deposition may require upper launch to avoid the absorption at fast ion resonances. Finally, LHCD shows very good off-axis current drive efficiency, but tends to be absorbed in the outer part of the plasma. By tailoring appropriately the spectrum (narrow  $N_{\parallel}$  range) this situation is predicted to improve and give access up to about half radius, but this scheme needs to be validated before becoming a serious option. An important lesson learned for DEMO2 is that the operational point must be individually optimized for the chosen CD system, since for example NBCD and ECCD react differently to an increase in  $Z_{\text{eff}}$ . This strategy will be followed up in further optimisations. However, it is already clear that the physics analysis sets important boundary conditions for the design of the H&CD systems and must go hand in hand with the engineering design.

### III) Design and R&D for DEMO HCD systems

#### III.1) Design approach

The missions of Work Package (WP) HCD are to conduct system design based on the use of electron cyclotron (ECW), ion cyclotron (ICW) waves and neutral beam injection (NBI). A lower hybrid system is not included in the workplan of WP HCD. Presently the work is focusing on the DEMO 1 baseline called EU-DEMO1 2015. The main physical parameters are given in Table 1. For a DEMO reactor, the HCD system must be fully integrated in the machine design and satisfy stringent criteria on availability, safety, environmental aspects (use of materials, which do not require geological repository), remote handling (RH), and impact on the Tritium Breeding Ratio (TBR). Overall, the final TBR of DEMO should be in the order of 1.1. To achieve this value, due to openings for diagnostics, limiters, fuelling lines and HCD antennas and feeders and the modifications of the breeding blankets due to integration, the overall decrease,  $\Delta\text{TBR}$ , of the TBR for all HCD systems should be in the order of 0.04. This value is dependent on the design of the penetrations and selected technology for the breeding blankets. On the technological side, the activities are twofold: on a system level, develop and integrate into DEMO1 baseline the three heating methods and, in parallel, conduct the R&D to advance the technology to fulfil the DEMO requirements such as RAMI or minimization of the recirculating power. From a strategic point of view, until the end of 2020, the work on DEMO1 should be considered as a pre-conceptual phase: the task of WP HCD is also to follow the proposed concepts and to determine their impact on the design of the HCD systems.

Since at present the heating mix and all the functions of each heating system are not fully defined, in order for the design work to be performed, it is assumed that for each system (EC, IC and NBI) the power delivered to the plasma should be 50 MW. For EC an additional 10 MW is considered for NTM control. Except for the NBI, where the power per injector is about 17 MW [8], both EC and IC systems have modularity (sources/amplifiers power) to cope for different power requirements. It is foreseen that by the middle of the DEMO Conceptual Phase (by end of 2024) the assessment leading to the choice of the heating mix will be performed based on physics scenarios, design of the heating systems which takes into account safety, RAMI, remote maintenance aspects and the results of the R&D programme.

In order to facilitate the reading of the different sections below, we present a cut out of DEMO, showing the radial equatorial port and the vertical ports. If needed (e.g. in the case of NBI) other types of port extensions may be required.

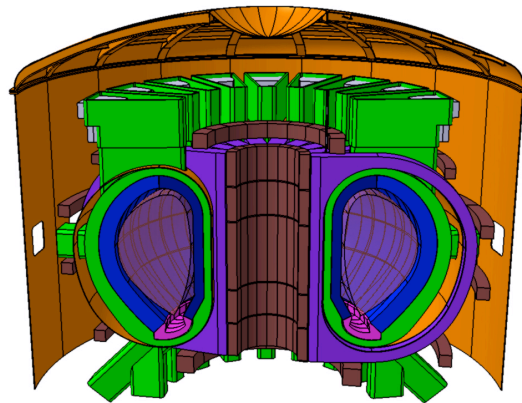


Fig. 1 Cut out of DEMO showing the equatorial ports and the vertical ports. Other port extensions could be requested

### III.2) EC system

For EC [9] various options for the system from the gyrotrons to the launchers are considered. Based on the magnetic field of DEMO1 (Table 1), in order to fully benefit from the development made for ITER and for other European programme, the gyrotron performances are dual frequency tubes (170 GHz and 204 GHz) at 2 MW RF output power. The system studies are assessing different options of transmission lines and launchers. Regarding the transmission system, both options of evacuated wave guide system and evacuated quasi-optical transmission lines are under consideration, taking into account the experience gained in the frame of ITER works [10] and from the operation of W7-X ECW. In the present phase of studies, two concepts of launchers are under studies: antennas based on the remote steering concepts and ones using the truncated waveguide, requiring step-tunable gyrotrons. RAMI considerations are used for determining the number of clusters, in which a cluster consists of a power supply, power switches for each gyrotron, a collective transmission line and launchers. Assuming that the desired availability should be closed to 100 %, redundancy is foreseen. The system is split into 4 +1 backup clusters delivering power to the equatorial port for heating and two vertical/upper launchers dedicated to NTM stabilisation (with less launched power). Each of the cluster having 8 gyrotrons delivering 2 MW each, to insure a total power into the plasma of 50 MW and 10 MW for NTM stabilisation, while taking into account the power loss along the transmission. A view of an antenna system installed in the equatorial port is shown in figure 1. The integration of the EC launcher in the blanket, considerations on loads specifications and remote handling are described in [11]. A first (and very rough) estimate of the decrease in Tritium Breeding Ratio,  $\Delta TBR$ , ranges from 0.035 [11] to 0.0175 [12], depending on the design of the antenna and its integration in the blanket. This important point will be addressed further.

Since the PPPT program is still in a pre-conceptual phase where the final parameters of DEMO1 and DEMO2 are not yet defined, advanced high frequency (240 GHz) high power (up to 2 MW) gyrotrons are under development to avoid de-scoping of potentially interesting options, especially in view of a steady state DEMO2 where CD functions are important and therefore may require high up shift value of frequency (Wave frequency [GHz] = up shift value \*  $28 * B_T$  [T]) [14]. Having a step tunable gyrotron could also alleviate the requirements for the RF antenna, therefore the programme also includes their development and the necessary large-diameter CVD diamond-disc Brewster-angle window. In the frame of developing advanced concept of gyrotron, the programme is also pursuing the development of novel methods to increase the efficiency of multi-stage depressed collectors [15] in order to decrease the recirculating power in a DEMO plant.

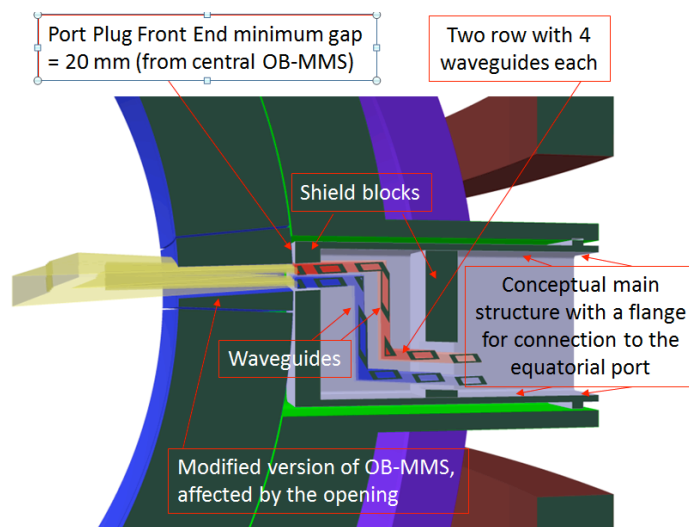


Fig. 1. Cut out showing an antenna integrated in an equatorial port

### III.3) IC system

For IC wave [13], the need to reduce the number and area of the penetrations in the blanket and to avoid high power density system leads to the choice of distributed antenna of the travelling wave type and covering the full  $360^\circ$  toroidal extend (Fig. 2). From an integration point of view, this concept offers the following advantages: minimum impact on the blanket function (neutron shielding and tritium breeding), modularity, matching the blanket modularity (to facilitate RH), and no need of extra openings in the vessel. This concept allows for an improved coupling by being able to work with low  $k_{\perp}$ , the avoidance of the occurrence of sheaths and impurity production. Using Monte Carlo Neutron Particle (MCNP) code, the decrease  $\Delta$ TBR of the TBR is of the order of 0.006 for the antenna without feeders. Solutions are explored, which match the modularity of the antenna to the one of the blanket. The design of the RF feeders and their penetrations through the vertical ports and their TBR impact are under way [14].

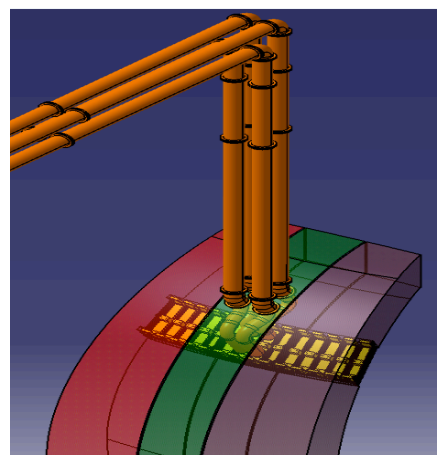
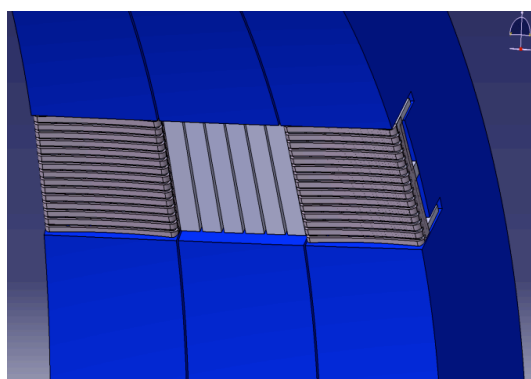


Figure 2. Left: View of a part of the IC antenna without the Faraday screen (center) and the Faraday shield (on each sides). Right: Schematic view of the RF feeders which will penetrate using part of the vertical port of DEMO

### III.4) NBI system

For the DEMO NBI working in the range of  $<1$  MeV, the studies [8] are concentrated on elements such as the neutralizer, the losses in the accelerators (minimization of stripping loss by maximization of the vacuum pumping) and the beam duct (the part which connects the NB injector with the tokamak chamber), which have impact on the NBI efficiency. Compared to the ITER NBI system (1 MeV voltage), due to RAMI considerations, DEMO NBI is considering a slightly reduced beam voltage (800 keV). The NBI system is shown in Figure 3. As described in Ref [8], the design parameters of the NBI will allow with three NBIs the deposition in the plasma of 50 MW. To increase the efficiency of the injector and the power of the neutral beam, photoneutralisation concepts are being considered in several laboratories and are discussed in details in [8]. Other important issues are the design of the beam source, the beam shape (“blade shapes”, which are compatible with both, photoneutralisation and gas neutralizer), vacuum pumping (such as non-evaporated getter or Hg pumps, which are compatible with the DEMO operation) and the Cs management or avoidance in the source. The integration of the NBI systems is under way in the frame of DEMO1. The beam will penetrate in the plasma through specially designed tangential ports and is injected in the co-direction. Since in DEMO1, CD is not a driving requirement and after consultation with the Breeding Blanket design group, an optimal angle of tangency is selected to be 30 degrees. In order to minimize the size of the penetration in the blanket, the beam is focused at the breeding blanket opening and not in the plasma center. The decrease of TBR is in the order of 0.006 to 0.018 for  $50\text{MW}_{\text{inj}}$ , i.e. 3 NBIs [13].

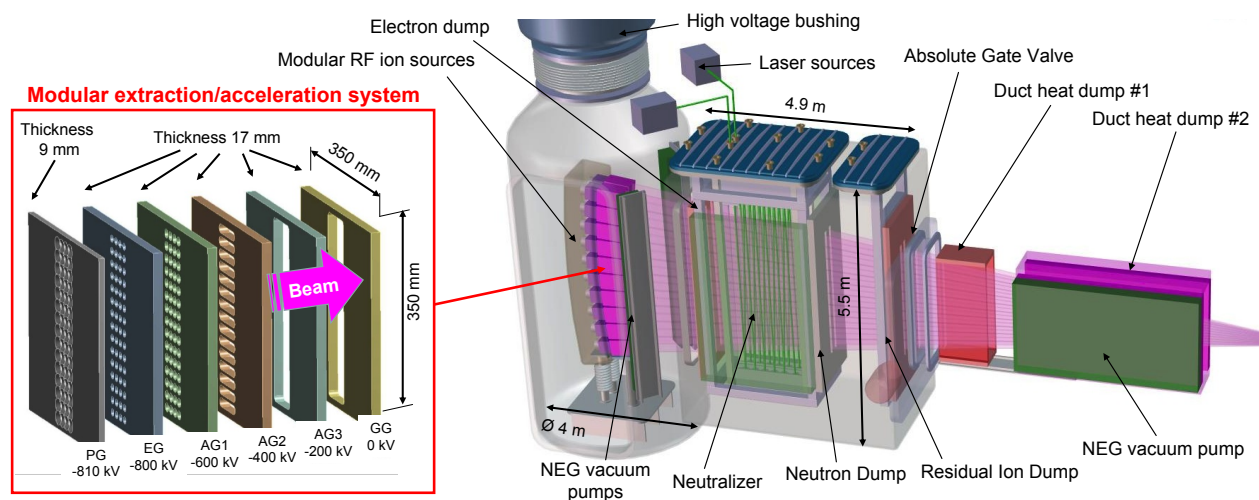


Figure 3. Schematic of the NBI under study for DEMO1

### III.5) System engineering considerations

Criteria for RAMI are important aspects for the design of any HCD system. However, the experience in RAMI for the new HCD concepts as shown before is limited, if not at all for some components, non-existent. The WP HCD is developing a methodology, which could be used as a common basis during the design of the three HCD systems and for the determination of the required redundancy of sub-systems.

Although the present activities are in pre-conceptual phase, an integrated approach is mandatory to insure that the interface requirements and their fulfilments. Part of the activities of WP HCD is oriented in this direction as well.

## IV) Conclusion

In the design of HCD for DEMO, many constraints must be taken into account. The most prominent one is the availability of the systems, since a failure of a system may terminate the plasma pulse and prevent the supply of electricity to the grid. On the other hand, as highlighted above, the requirements on the systems and

their advanced characters will pose huge challenges to designers. The goal of the R&D of the WP HCD is to develop, as much as possible the technology necessary to decrease the risk, by having design options in parallel developments and collaboration with other fields such as safety, fuelling and pumping, breeding blanket design, remote maintenance, materials and control.

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