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The engineering design and R&D of auxiliary heating systems and their sub-systems is a key activity in the frame of the present conceptual design phase for a first of a kind DEMOnstration Fusion Power Plant in order to develop a system capable of achieving and controlling burning plasmas. In the frame of the EU DEMO reference design, the R&D activities consider the injection of about 50 MW of Electron Cyclotron (EC) power to support and assist different plasma phases. As the project is still in the conceptual phase, a range of options for gyrotrons, transmission lines and antennas is under assessment taking into account the guidelines for the integration of EC system in a nuclear reactor and a maximal achievable reliability and availability of the EC power during operation.

Keywords: DEMO, Heating and Current Drive, Launcher, Transmission Line, Gyrotron.

1. Introduction

One of the priorities of the European Roadmap to Fusion Electricity [1] is to demonstrate the capability of the DEMO fusion reactor to deliver net electricity for the grid. In the present EU strategy the DEMOnstration Fusion Power Plant is considered to be the first of a kind fusion reactor to cover the distance between the ITER experiment and the commercial Fusion Power Plant (FPP) [2]. The main purpose of DEMO is to address and resolve the physics gaps and technical issues of a future FPP, to convert the heat into electrical power output (~500 MWe) with high reliability/availability and to achieve tritium self-sufficiency with an adequately margin in order to guarantee a closed fuel-cycle for its own operations [3, 4]. Different DEMO design concepts are under investigation which range from a 2 hours pulsed tokamak (DEMO 1) a 'conservative' baseline machine based on the ITER (Q=10) expected performance to a more 'advanced' steady-state machine (called DEMO 2) with even more advanced physics and technology assumptions. The EUROfusion Consortium is conducting the DEMO conceptual design on different aspects in charge of several Work Packages (WPs). The WPHCD (WP Heating & Current Drive) addresses the engineering design and the R&D of the auxiliary heating systems: Electron Cyclotron Resonance Heating and Current Drive (ECRH&CD) [5], Neutral Beam Injection (NBI) [6] and Ion Cyclotron Resonance Heating (ICRH) [7]. The first step of the conceptual design for the EC system is the identification of the physical requirements demanded to the EC system. The different tasks of the EC system foreseen with the required power and deposition localization in terms of normalized radius ρ are listed in Table 1 based on the EU DEMO1-2015 baseline [8]. In the present pre-conceptual design phase each heating system is considered with a target power of 50 MW delivered to the plasma, noticing that EC design value could be larger if wished according to the calculation for plasma current ramp-up/-down phases [9]. The EC power dedicated to NTM control is considered in addition to the 50 MW. The required EC power in each phase of DEMO pulse must be guaranteed at maximal reliability and availability because a fault in the system would mean a pulse termination with an interruption of electricity production. The present baseline of DEMO will be updated according to progress of the work and a final decision on the EC frequency will depend on the final physics parameters of the plasma. Therefore as a first reference, two possible frequencies have been selected to perform the conceptual design analysis of the DEMO EC system according to the new 2017 baseline, which was released in June 2017: 170 GHz for heating (compatible with ITER) and 204 GHz for current drive, the latter corresponds to a moderate so-called frequency upshift of 1.2 factor.

Table 1. DEMO EC tasks and operation modes with required powers and deposition locations.

EC Task	Mode	Power	Deposition

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		[MW]	$[\rho]$
Assisted Breakdown	Heating/CD	6-10	<0.3
I_P ramp-up and L-H transition	Heating/CD	50-(80)	<0.3
Main Heating	Heating	50	<0.3
Sawtooth control	CD	2-10	<0.3
Disruption control	CD	10	0.7
NTM control (q=2; q=3/2)	CD	>15	0.865; 0.7
I_P ramp down	Heating	40	0.3-0.5

2. Gyrotron R&D and Advanced Developments

The initial requirements for the gyrotron are: (i) an estimated output power significantly larger than 1 MW (present target 2 MW), (ii) an efficiency better than 60% and (iii) an operating frequency at 170 GHz (ITER), 204 GHz or even close to 240 GHz (depending on the final definition for the aspect ratio of the DEMO tokamak related to the final toroidal magnetic field and whether a steady-state machine which a high amount of plasma current driven by EC is aimed for). "Multi-purpose" (multi-frequency) and frequency step-tunable gyrotron concepts are under investigation to fulfill the different possible EC tasks such as heating, current drive and frequency steering of the RF beam using the same type of gyrotron. "Multi-purpose" operation at the natural frequencies for RF transmission through the RF output window, corresponding to multiples of the half-wavelength of the single Chemical Vapour Deposition (CVD) diamond disc (equivalent to steps of ~34 GHz considering a dielectric constant $\varepsilon_r = 5.67$ and a window thickness of 1.851 mm (same as ITER), allows the EC operation at different discrete frequencies for heating and current drive (e.g. at 136/170/204/238 GHz) without the need for a broadband window. "Frequency step-tunability" shall offer fast stepping of the operating frequency (in seconds) in leaps of 2-3 GHz over a bandwidth of approximately 10 GHz using a broadband RF output window technology (preferably a Brewster angle window) for fine tuning of the absorption layer in the tokamak [10].

So far the initial feasibility studies of a possible future DEMO gyrotron include the EU coaxial-cavity and, as a possible fallback solution, the conventional hollow-cavity gyrotron technology, e.g. used for W7-X and ITER. So far, the research on both options was aiming on finding the maximum output power versus the stability in operation. Considering the coaxial-cavity and the hollow-cavity gyrotron technologies generic design strategies were developed and applied to find the optimum operating mode for multi-frequency and fast frequency step-tunable operation [11,12]. Based on the theoretical studies, the coaxial-cavity technology is seen as the leading technology for future multi-megawatt CW gyrotrons. Having identified the most promising gyrotron technology, the research on the coaxial-cavity technology is focusing on the most critical issues, the thermal loading of the cavity wall and the coaxial insert together with the influence of the misalignment of the critical components, particularly the coaxial-insert considering an operation at up to 240 GHz.

The theoretical studies are accompanied by experiments, including an upgrade of the existing 2 MW 170 GHz short-pulse (ms-range) pre-prototype to pulse lengths up to 1s [13]. Advanced cooling concepts are under study [14,15]. Having applied the newly developed general guidelines for any MIG design [16] the manufacturing of a new type of Inverse Magnetron Injection Guns (IMIG) [17] is ongoing that allows a larger emitter radius and a significant improved cooling possibilities, therefore increased output power or, alternatively, a more compact size of a future gyrotron. In parallel, a new conventional type MIG with a new type of emitter ring with coated ends is under manufacturing. Using this type of emitter ring the influence of the manufacturing tolerances and the misalignment on the beam quality is minimized [18]. In future, FULGOR, the new gyrotron teststand at KIT shall allow the development and verification of gyrotrons with output powers of up to 2(4) MW CW. Additionally the use of multi-stage depressed collectors will be possible [19]. A superconducting (SC) magnet of 10.5 T will allow operation of future gyrotron at frequencies up to 240 GHz.

Frequency tuning in steps of 2-3 GHz requires the use of a broadband output window. The preferred option is a CVD-Diamond disc Brewster-angle window. Successful operation at output power level of 1 MW at short pulses (ms-range) was demonstrated in [20] already using a diamond disc with 140 mm large diameter (corresponding to a WG diameter of 50 mm). For multi-megawatt CW operation, advanced with a step-frequency tunable 1 MW short-pulse (ms) cooling concepts, new brazing technologies, and, in particular, diamond discs with larger diameter up to 180 mm (corresponding to a WG diameter of 63.5 mm) are required [21].

To minimize the recirculating power in the DEMO plant a total efficiency of more than 60% is required for a future DEMO gyrotron. Assuming a free-running oscillator and a typical electronic efficiency of 35% in the interaction between the electromagnetic wave and the microwave, multi-stage depressed collectors (MDCs) must replace today's single-stage depressed collectors used for recuperation of the spent electron beam energy. For future DEMO gyrotrons two different concepts for multi-stage depressed collectors (MDCs) are under investigation [22, 23, 24]. A first approach uses the non-adiabatic demagnetization concept [25] while in the second concept the E×B drift to sort and drift electrons towards the electrodes according to their initial velocities [26].

3. EC System Conceptual Design

The primary driver of the conceptual design is to deliver 50 MW of EC power to the plasma (plus the required amount for NTM control mentioned before) to fulfill all the tasks demanded to the heating system and summarized in table 1 with an ideal reliability of ~100% as explained in Sec.1. This ambitious achievement can be obtained both with high reliabilities of the subsystems and their components and by providing sufficient redundancy with

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the use of modularity allowing the replacement of the failing units while still operating the whole system. Therefore the EC system is organized in clusters with gyrotrons fed for each cluster by only one High Voltage Power Supply, one Multi-Beam TL (MBTL) considered as only one subsystem (even if composed by separate WGs) and antennas. Based on the EU DEMO1-2015 baseline, a preliminary study of the reliability requirement has been conducted [23] assuming the target of 50 MW delivered and a reliability of 98% for the 2 MW gyrotron and 99,9% for antenna and TL (with 10% of losses, see section 3.1). The Mean Time Between Failures (MTBF) is the reference figure of merit and for a DEMO discharge of 2h 1000 pulses between two major faults of the EC system mean an MTBF of 2000 h (99,9% of reliability). The reliability analysis based on the EU DEMO1-2015 baseline led to an optimized number of 4 clusters + 1 in stand-by with 8 gyrotrons and antennas for each cluster (7 in operation +1 in stand-by) for main tasks and one cluster dedicated to NTM stabilization. For the EC system it is considered therefore a total number of 40 gyrotrons (28 of them in operation) and MBTLs, each of them connected with 8 antennas.

The multi-options approach foresees a system fully integrated in the reactor plant design with different options for gyrotrons, TL and antennas under assessment. They have (i) to fulfill the stringent safety criteria, (ii) to be compatible with Remote Maintenance (RM), (iii) to minimize the apertures into the blanket in order to reduce the impact on the Tritium Breeding Ratio (TBR), (iv) to satisfy the target RAMI (Reliability, Availability, Maintainability and Inspectability) requirements and (v) to involve the modularization of components pursuing economic improvement.

3.1 Transmission Line

A target efficiency of 90%, power handling of 2 MW CW, multi-frequency (or broadband) capability and tritium compatibility are the main requirements demanded to DEMO EC TL. Two TL options are adopted on the present experimental devices: Evacuated corrugated Waveguide (EWG) at DIII-D, TCV and Quasi-Optical (QO) TL in air at W7-X. The EWG is also the solution adopted for the ITER. DEMO will be certainly able to choose EWG for its TLs and benefit of the ITER R&D and test as well as the recent W7-X experience. Considering the large number of TLs (~40 as discussed above) the MBTL like the one in use at W7-X could be a very attractive solution for DEMO because it is a compact arrangement capable to reduce the complexity of the system and to save space and components, provided that the distance from the gyrotrons to the tokamak is not excessively long. The drawback of this option is that the power transmission in air is not compatible with a nuclear plant for tritium segregation (especially in case of failure in the torus window). To maintain the advantages of QO TL and to satisfy the safety requirements it is imagined for DEMO an Evacuated QO (EQO) TL, a MBTL enclosed in a vacuum vessel.

The reference design is based on confocal mirrors layout where the single TL unit is composed by a couple of mirrors, one plane and one shaping, forming a dogleg for TL bend and a straight path where 8 beams of one cluster propagate alternatively crossing or parallel to each other. One pumping system is foreseen for each unit. All mirrors are water-cooled.

A preliminary analysis to verify the feasibility of this TL proposal has been carried out. A single circular oversized focusing mirror is considered to transmit up to 8 single overlapping beams arranged on vertices of a regular heptagon and the eighth in the center. The minimum mirror radius has been set $r = 1.75w + 90$ mm where w is the beam radius $w = w_0\sqrt{1+\left(\dfrac{\lambda L}{2\pi w_0^2}\right)}$, with $w_0 = 20.43$ mm being the beam waist at the aperture of a WG of a diameter of 63.5 mm, λ being the wavelength, 90 mm being the distance between a vertex and the center of the heptagon (figure 1 right) and L the characteristic length of the system, defined as the distance between two focusing mirrors. Considering 8 Gaussian beams of 2 MW each one (assuming a conservative mix of 50% for both polarization), 45° incident angle on a copper surface, the theoretical absorbed power density evaluated in different mirror points at 170/204 GHz is function of L, being the diameter of mirror depending on relative distance, and has <0.4 MWm^{-2} for $L >$ ~5/6.5 m and <0.3 MWm^{-2} for $L >$ ~10/11 m (figure 1 left).

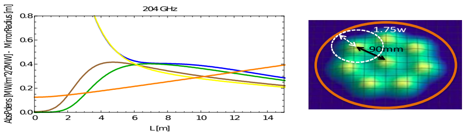

Fig. 1. Left: the absorbed power density in function of L for different points of the mirror surface (see right) at 204 GHz. In orange the beam envelope radius. Right: an example of 8 beams disposed on a mirror surface with the beam envelope (orange circle).

An estimation of losses has been accomplished for 150 m of generic EQO at two different L, 8 m and 12 m, and for both 170 GHz and 204 GHz. Table 2 shows theoretical ohmic losses estimation for a TL of several ideal surface copper mirrors with 90° bends: the incident wave polarization can be chosen appropriately (if the bends are kept in one plane along the whole TL path) to halve the losses (saving 3-7% of 50 MW means sparing 1-2 gyrotrons). The details of other loss contributions as the beam truncation, mode conversion and misalignment are reported in [5]. Considering the worst case (L=8 m, 170 GHz) the overall transmission efficiency results in the range 88%–91%, close to the initial DEMO requirement (90%) and to the EWG estimated efficiency (88–90% at 170 GHz, depending of the number of mitre bends).

Table 2. Ohmic losses estimation for ~150 m of EQO TL.

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Absorption on mirrors [#]	L=8 m [40]		L=12 m [28]	
H-plane, inc. angle 45º [%]	3.18	3.47	2.23	2.45
E-plane, inc. angle 45º [%]	6.26	6.83	4.42	4.83
Frequency [GHz]	*170*	*204*	*170*	*204*

A preliminary analysis of the cost has been based on the contribution of mirrors, vacuum envelope and pumping system. The latter two are based on recent quotations provided by private companies whereas the mirror cost is taken from W7-X [24] and rescaled with dimensions. The cost per meter estimation has been reported as a function of L only and normalized to the EWGs cost (referred to 2009 ECRH4JET project [25]). With r = 1.75w + 90 mm the cost is < 0.6 for L > 2 m. After ~ L = 8 m the cost reaches a lower saturation (< 0.4) because the reduction of number of mirrors is counterbalanced by the increased mirror size. If one considers the larger radius (r = 2w + 90 mm) the cost increased by ~10-15%.

An initial proposal of the TL layout is being developed with work package Balance of Plant (WPBoP) [26]. In a single Radio Frequency (RF) building two clusters (for a total of 16 gyrotrons) are hosted. The output multi-beams, after a single-beam TL section, are combined into two MBTLs, routed in the basement of the plant in a dedicated duct to allow a straight path towards the tokamak thus minimizing the TL length and avoiding any interference with other buildings. Before the Assembly hall the MBTL directs the beams towards the equatorial level with a vertical section outside the Tokamak building. After a 90º bend the MBTL carries on crossing the Tokamak building. At the end of MBTL the beams will split again into single-beam TL and directed to a single plug-in launcher composed by 8 independent antennas per port.

The level of the Stray Magnetic Field (SMF) at the gyrotron position defines the minimum distance between the RF buildings and DEMO hall. In fact the gyrotron can operate only at prescribed SMF level, in both radial and vertical directions. Exploiting the axisymmetric geometry of the tokamak, the magnetic field B can be estimated as a function of distance D from the torus center using Biot-Savart's law by solving the elliptic integrals. The considered contributions at SMF are the plasma current I_P the currents of the five central solenoid coils and six poloidal field coils. For R>>a (where R is the DEMO major radius and a is the coil radius) the magnetic field generated by a single coil can be approximated to the field produced by a point dipole. The plasma current I_P has been considered as an electric dipole with coordinates R = 9.072 m and z = 0 m. The geometry and coil system relies on the EU DEMO1-2015 baseline. The gyrotron requirements prescribe for the axial component B_z < 10 G and for the radial component B_R < 2 G. The radial constraint is the most dangerous (especially at collector level) since a DC current can easily suppress the axial component applied to the dedicated collector coils. A map in (R,z) coordinates for B_z and B_R at 2, 5 and 10 Gauss during different phases of a typical DEMO discharge (pre-magnetization (without I_P), Start and End of Flat-Top, plasma ramp-up and ramp-down) and during a Vertical Displacement Event (VDE) has been evaluated. Figure 2 shows the worst case result: the red arrows show the limit of the safe area according to the requirements to place the gyrotron building. The overall result suggests a safe area to place the RF building at equatorial plane or underground level.

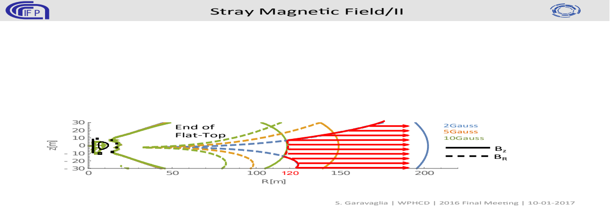

Fig. 2. (R,z) map for B_z and B_R at 2, 5 and 10 Gauss during End of Flat-Top phase. The red arrows show the safe area to place the RF building.

3.2 Antenna

A design of a launching system with sufficient flexibility, without movable parts in the proximity of the burning plasma and including shielding against neutron bombardment is mandatory to deliver the required amount of power at different deposition locations. Two designs are under assessment: a) Remote Steering Antenna (RSA) or b) a simpler Truncated Waveguide Antenna (TWA) with the need to work in conjunction with a step tunable gyrotron. A general assessment based on beam tracing code TORBEAM [27] and a self consistent plasma scenario for DEMO1 obtained with ASTRA [28] code has been performed to evaluate launching performance and plasma accessibility from a RSA located in different points situated in a poloidal section. Five different launching points from the equatorial port and different frequencies (from 140 GHz to 240 GHz, with steps of 10 GHz) have been scanned and for each of them the identification of an antenna axis and a steering plane capable to cover the widest range of deposition locations has been seek. The possibility to cover the EC tasks of Table 1 using both selected frequencies is demonstrated in [29]: 170 GHz can be efficiently used for NTM control and for central or off-axis heating while the 204 GHz results preferable for central CD.

In figure 3 an example of the extensive study done is reported: a map of the beam tracing results for an Equatorial Port Plug launching point in terms of deposition location accessibility ρ and total driven current I_{CD} as a function of the two angles α and β, for 170 GHz and launched beam with w_0 = 20.4 mm. The overall results point out the most promising options [29] on which further refinements will be applied. It needs to be mentioned that a good steering plane with large coverage and total driven current I_{CD} for one frequency might not be optimal for other frequencies. The highest frequencies are more efficient for current drive at inner deposition. The NTM control requires current density with narrow profile in outer region of the plasma that can be reached by moving the launching point towards a higher position with respect to the equatorial plane. This analysis shows smaller deposition widths, indicating the possibility of an upper launcher. In addition, for NTM control, the TWA option will be investigated at fixed orientations exploiting multi-frequency and step tunability options of the gyrotron

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for the fine-tuning of the deposition.

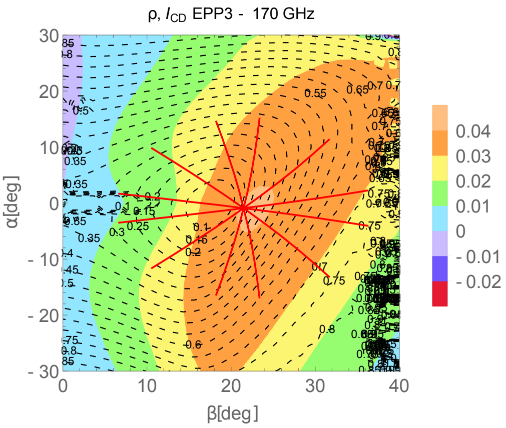

Fig. 3. Contour plot for normalized deposition location ρ (black dashed curves) and total driven current I_{CD} (color code, MA/MW) as a function of the injection angles (α, β) with different possible steering planes (red lines centered on α_0=20°, β_0=20°, corresponding to a given steering plane orientation, with $\Delta\gamma$=±15° range).

The implementation of the antenna into the tokamak equatorial plug is the subject of an extensive engineering integration study, with three concepts under assessment: a Blanket Separated Design, where the port plug stops behind the Outboard Multi-Module Segment (OB-MMS), a Blanket Integrated Design, where the port plug penetrates the OB-MMS up to the plasma [34] and a Blanket Divided Design (BDD), where the port plug penetrates and divides the OB-MMS into two parts. The RSA option, a straight square corrugated WG, has different constraints to be taken into account. First the good beam characteristics can be obtained for a limited angular range (max. ±10° up to ±15°) [35] and this range affects the width of the required apertures on the blanket modules. Moreover the total RS length is directly connected with the beam frequency f and WG size s: for s = 75 mm and f = 170 GHz (204 GHz) the prescribed length is ~13 m (~15 m). Finally the RS WG routing within the plug must have mitre bends in order to provide dogleg structures against neutron streaming not too close to the WG termination. Bends and doglegs are allowed only in the plane perpendicular to the chosen steering one. Starting from these constraints, different setups have been evaluated and the most promising are a single stacked row arrangement for the 8 antennas with central injection at the port aperture and providing a steering in the poloidal direction and an arrangement with 2 rows x 4 stacked antennas. With the new DEMO baseline 2017, these studies have to be re-evaluated to take into account less but larger ports (16 compared to former 18 and the impact on neutronics issues, mechanical aspects on breeding blanket, TBR, bioshield interactions and interfaces. A preliminary evaluation of the impact of the minimum apertures required by EC launchers on the blanket in terms of TBR degradation has been performed and reported in [34, 36].

4. Conclusions

The status of the DEMO EC system conceptual design with gyrotron R&D and advanced developments is presented and discussed. A design method compatible with a fusion reactor has been developed and is progressing. Future integration work will be focused on the new EU DEMO1-2017 [4].

Acknowledgments

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