Progress in conceptual design of EU DEMO EC system

Saul Garavaglia[1,*], *Alex* Bruschi[1], *Thomas* Franke[2,3], *Gustavo* Granucci[1], *Giovanni* Grossetti[4], *John* Jelonnek[5], *Alessandro* Moro[1], *Emanuele* Poli[2], *Natale* Rispoli[1], *Dirk* Strauss[4] and *Quang Minh* Tran[6]

[1]Institute of Plasma Physics “P.Caldirola”, National Research Council of Italy, Milan, Italy
[2]Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, Garching, Germany
[3]EUROfusion Consortium, Boltzmannstr. 2, D-85748 Garching, Germany
[4]KIT, IAM-AWP, Postfach 3640, D-76021 Karlsruhe, Germany
[5]KIT, IHM, Postfach 3640, D-76021 Karlsruhe, Germany
[6]Swiss Plasma Center, EPFL, CH-1015 Lausanne, Switzerland

Abstract. Since 2014 under the umbrella of EUROfusion Consortium the Work Package Heating and Current Drive (WPHCD) is performing the engineering design and R&D for the electron cyclotron (EC), ion cyclotron and neutral beam systems of the future fusion power plant DEMO. This presentation covers the activities performed in the last two years on the EC system conceptual design, as part of the WPHCD, focusing on launchers, transmission lines, system reliability and architecture.

1 Introduction, physical requirements and design guidelines

According to the European Roadmap [1] the main purposes of the Demonstration Fusion Power Plant (DEMO) are to deliver electricity to the grid and to allow Tritium self-sufficient breeding in order to assure autonomy for its own operations. The EUROfusion consortium is conducting detailed studies on different aspects of DEMO power plant and the Work Package Heating and Current Drive (WPHCD) is performing conceptual studies and the engineering design for the electron cyclotron (EC) [2], ion cyclotron and neutral beam heating systems and R&D for gyrotron source and NB injector. The primary objective is to deliver a feasible concept design of the EC system fully integrated in the machine design, satisfying the stringent safety and Remote Maintenance (RM) criteria and minimizing the impact on the Tritium Breeding Ratio (TBR). Various options for gyrotrons, Transmission Lines (TL) and launchers are under assessment taking into account the integration in a nuclear environment and target RAMI (Reliability, Availability, Maintainability and Inspectability) requirements specific for a power plant.
On the one hand, EU DEMO1-2015 is the present baseline design, a 2 h pulsed machine, with an aspect ratio (AR) of 3.1, toroidal magnetic field of 5.7 T and about 50 MW external heating and a minor role of auxiliary plasma current drive (CD). On the other hand, EU DEMO2-2015 is a steady state machine (i.e. a more advanced concept) where CD is significant to sustain the plasma current. Table 1 summarizes the main basic tokamak parameters derived from the PROCESS code [3]. The starting point of the conceptual design is the identification of the physical requirements demanded to the EC system for EU DEMO1-2015.

Table 1. Summary of major tokamak parameters for DEMO1 and DEMO2 (April 2015).

	EU DEMO1 2015	EU DEMO2 2015
Major radius [m]	9.072	7.5
Minor radius [m]	2.927	2.885
Aspect Ratio	3.1	2.6
Toroidal field [T]	5.7	5.627
Plasma current [MA]	19.6	21.6
Heating power [MW]	50-100	133
Fusion Power [MW]	2037	3255
q_{95}	3.247	4.405
Number of TF coils	18	18
Pulse duration [hours]	2	continuous
$<n_e>[10^{20}\ m^{-3}]$	0.8	0.9
Peaking: $n_{e0}/<n_{e,vol}>$	1.27	1.397
$<Te>$ [keV]	13.1	18.1
Peaking: $T_{e0}/<T_e>$	2.1	1.9
Surface area [m^2]	1428	1253
Plasma volume [m^3]	2502	3255
Fraction of $I_{BOOTSTRAP}$	0.347	0.611
Fraction of I_{OHMIC}	0.557	0
Fraction of I_{CD}	0.096	0.389

The main EC tasks are reported in Table 2 with the required power and deposition localization in terms of normalized radius. The preliminary studies suggest that

* Corresponding author: garavaglia@ifp.cnr.it

4-6 MW are needed to sustain the DEMO breakdown and start-up and point out that an oblique injection is desirable to exploit the polarization conversion of non-absorbed power at inner wall. For plasma current ramp-up preliminary results with the METIS code [4] indicate 50 to 100 MW of additional power are needed to reach robust L-H transition. During plasma flat top presently 50 MW of HCD power is considered, assuming in this paper that EC providing the full amount of this power, with both oblique or perpendicular injecting angle. The later DEMO HCD mix selection may change these EC power requirements. During the burning plasma the EC system is also required for MHD control: 10-15 MW of EC power is dedicated for Neoclassical Tearing Mode (NTM) and sawtooth control. For the safe plasma current ramp-down up to 40 MW of off-axis EC power is considered by the simulations with JINTRAC code [5] to avoid edge cooling and widen the current profile keeping plasma internal inductance lower.

Table 2. Main DEMO EC tasks with corresponding power required and plasma deposition location.

		Power required [MW]	Localization [ρ]	Mode
Assisted Breakdown		6-10	0-0.3	Heating /CD
Ramp up and L-H transition		50-100	0-0.3	Heating /CD
Main heating		50	0-0.3	Heating /CD
NTM control	q=2	10-15	0.7	CD
	q=3/2	10	0.4	CD
Ramp down		40	0.3	Heating

A total of 50 MW of EC power in addition to 10 to 15 MW EC power dedicated to NTM control in the plasma has been taken as reference for the present analysis; this total EC power must be guaranteed at maximal reliability and availability for all the DEMO pulses because an interrupted discharge will mean no electricity production.

The EC power will come from gyrotrons sources with estimated 2 MW output power per RF source, an efficiency of 60 % as target (cf. ITER 50 % [6]) and 98 % of unit reliability. Multi-purpose (multi-frequency) and frequency step-tunable gyrotrons are under investigation to fit all the physical requirements of Table 2. Multi-purpose aims at the gyrotron operations with different magnetic field configurations (slowly varying) and different possible frequencies for heating and CD corresponding to multiples of the λ/2 wavelength of the RF diamond window (~34 GHz for typical single-disc window thickness of ~1.8 mm), or, alternatively a broadband window design. The present reference frequencies are 170/204 GHz while the final operating ones will depend on the AR definition and toroidal related magnetic field and on the relevance of CD in operation, which typically requires an operation at about 1.2 times higher frequency compared to pure heating. On the other hand the availability of frequency step-tunable gyrotrons using a broadband RF output window (e. g. Brewster-angle window) which will enable the operation in steps of about 2 to 3 GHz (according to the different frequency distances of the operating modes) over an 10 to 12 GHz bandwidth will be compatible with the exploitation of a remote steering antenna concept for the launchers as presented at the EC-19 conference [7]. Equatorial (EL) and vertical (VL) launchers (without the use of switch between them) are required to deliver the RF power to the plasma through apertures into the blanket, that shall minimize the impact on Tritium Breeding Ratio (TBR). The EC system design must be as much simplified as possible with a single purpose demanded to each EC line, compatible with Remote Maintenance and involving the modularization of components to pursue economic improvement.

2 Launchers

A launcher with a sufficient flexibility and without movable parts in the proximity of plasma and blanket is required to deliver the required amount of power at different deposition locations. A Remote Steering Antenna (RSA), able to grant a continuous but limited steering range without mirrors in plasma proximity and Truncated Waveguide (TWG) launching a divergent Gaussian beam in a direction determined by waveguide orientation have been considered so far as launcher solutions. A general assessment based on previous DEMO baseline design (EU DEMO1 2012 with AR = 4.0) of the RSA capability has been performed in terms of launching performance, plasma accessibility, RS properties and potentialities for multi-frequency gyrotrons.

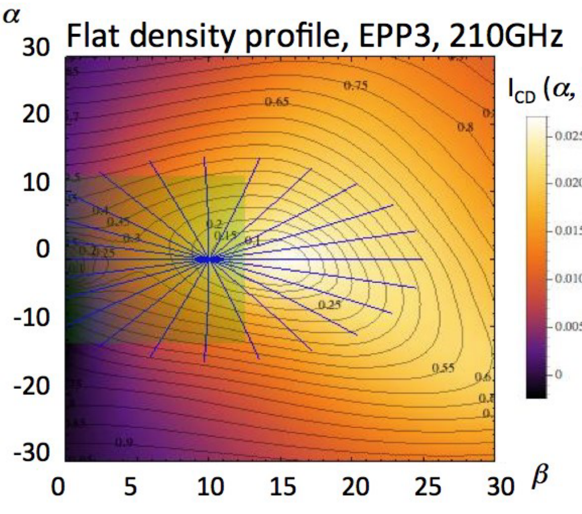

Fig. 1. Contour plots for normalized deposition location ρ and total driven current I_{CD} (MA/MW) as a function of the injection angles (α, β). The case of 210GHz frequency is shown, with launch point EPP3, the set of steering planes investigated (blue lines) and the port geometric constraints (shadowed area in green).

A possible integration into port plug and preliminary evaluation of required apertures for the RSA assembly was started and will be completed next year. In order to perform the analysis on possible launching configurations the beam tracing code TORBEAM [8] was used to simulate EC injection in several configurations. Five different launching points have been considered from both Equatorial (EPP) and Vertical Port Plug (VPP). The input parameters for TORBEAM runs are frequency f (170 ÷ 250 GHz), launched beam dimensions w_0 = 20.43 mm, toroidal angle β (0° ÷ 40°) and poloidal angle α (-45° ÷ 45° for EPP and 30° ÷ 60° for VPP) for two plasma profiles with density and temperature flat and peaked respectively. For a given scenario, frequency and launching point an optimal pair of reference injection angles (α_0, β_0) can be found and used to identify possible RSA planes and maximum steering ranges of application. As an example of the performed analysis Figure 1 shows the contour plot of normalized deposition location ρ and total driven current I_{CD} as a function of (α, β) angles□ All the results of beam tracing analysis are summarized in a map of I_{CD} for selected RSA direction and steering plane.

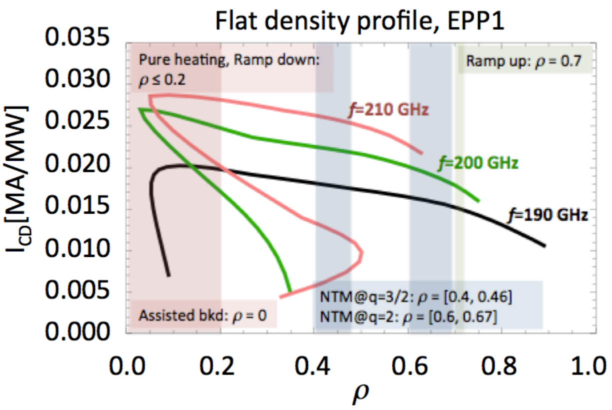

Fig. 2. Summary of total driven current I_{CD} (MA/MW) as a function of accessible deposition location ρ with the beam launched from EPP1 with α_0=-10°, β_0=17°, 6□□□□° for frequency in the range [190-210GHz]. Required EC functions are shown with rectangular areas.

In Figure 2 the most promising solution from EPP is shown where a complete coverage of deposition locations of EC functions is reached for f in the range 190 ÷ 200 GHz. Vertical port results show a better CD efficiency but reduced plasma coverage. A preliminary estimation of the minimum apertures required by the launchers on the Breeding Blanket (BB) has been calculated in order to allow a first evaluation of the impact on TBR of the EC launchers. A straight square corrugated WG has been considered as RSA termination with 63.5 mm size, steering range ±15 degrees, not protruding in the blanket region with 8 beams in two rows for EL and 4 beams for VL. The EC frequency assumed is 170 GHz and a Gaussian beam with 20 mm waist at the waveguide output. For each antenna, a space of 15x15 cm is foreseen to accommodate components, cooling and supporting structures and any auxiliary equipment needed at the port interior. The openings at BB level resulting are ~2.34 m^2 for 4 (+1 spare) ELs and 1.24 m^2 for 2 VLs (including 3 spare lines).
Tritium self-sufficiency is mandatory for DEMO and a net value of TBR ≥ 1.1 has to be reached including an additional margin, which account for modelling uncertainties and plant losses occurring during DEMO operations. Starting with the apertures calculated at the blanket level, the impact on the TBR for the five ELs is ΔTBR of ~0.004 (~0.313 %) and for the two VLs ~0.002 (0.166 %). These values look promising to reach the target value of 1.1 and with safety margins.

3 Transmission Line

On present experimental fusion devices two solutions for TL are adopted: Evacuated waveguide (EWG) in experiments as e.g. DIII-D, TCV and Quasi-Optical (QO) in air as e.g. used for W7-X. The main DEMO TL requirements are: target efficiency of 90 %, power handling of 2MW CW, multi-frequency (or broadband) capability and tritium compatibility. EWG is certainly contemplated a possible solution for DEMO but, since the WG components are still under development for ITER, the QO solution based on recent W7-X experience has been first considered. For DEMO the transmission of 10 beams in 2 Multi-Beam TL (MBTL) could be a very compact arrangement to reduce the complexity of the system and to save space and components. This solution is promising for the large number of DEMO beams provided that the distance is not excessively long. However the power transmission in air is not compatible with a nuclear plant for tritium segregation (in case of failure in the torus window). The QO TL solution requires therefore an additional containment structure to satisfy safety requirements. A proposed solution that takes the advantages of the QO line and in principle solves the safety issues is an Evacuated QO (EQO), a MBTL enclosed in a vacuum vessel. The reference design is based on mirror confocal layout where the single unit is composed by a couple of mirrors forming a dogleg for TL bend and a straight path where the beams propagate alternatively crossing or parallel to each other. One pumping unit is foreseen for each unit. The characteristic length of the system L is defined as the distance between the two focusing mirrors. In order to validate this proposal solution a preliminary analysis on different aspects has been conducted. The theoretical absorbed power density on a mirror surface as a function of L has been calculated considering 8 Gaussian beams, each one of 2 MW (assuming a conservative mix of 50 % of either polarization), incident with a 45° angle on copper surface on vertices of a regular heptagon and one in the centre. The minimum beam envelope radius has been set $r = 1.5w$+90 mm where w is the beam radius equal to $w = w_0*(1+(\lambda h/\pi w_0^2))^{1/2}$ and w_0 = 20.43 mm is the beam waist at the aperture of a waveguide of diameter 63.5 mm, λ the wavelength. The absorbed power density evaluated in different mirror points at 170/204 GHz is <0.3 MW/m^2 for L > 5/6.5 m and <0.2 MW/m^2 for L > 10/11 m) with minimum beam envelope radius of 0.2/0.24 m. The results are promising if compared with the same of ITER mirror mitre bend of ~2 MW/m^2. An overall estimation of theoretical losses for a generic EQO has been carried out starting from W7-X data [9]. Two different lengths have been selected, 100 m and 150 m, assuming L = 8 m. The transmission efficiency at 170 GHz is 88 % and 91 % for the respective lengths (the losses due to envelope wall were not considered), in according with the DEMO requirement of 90 % and in line with the same estimation done with ITER EWG components. Finally a preliminary cost analysis has been carried out evaluating three main contributions: mirrors, vacuum envelope and pumping system. The cost of components, based on recent quotations, has been related to distance L. The unit cost tends to be constant for $L > 6$ m and comparable with the EWG option.

4 System reliability and architecture

As a part of conceptual design phase the RAMI approach has been adopted and the impact of reliability requirement in a reactor like DEMO has been used as a guideline for designing the EC system architecture. The demanded reliability for an EC system should be as high as possible (assuming 99,9 % as a result of conservative consideration) and to reach this goal it is mandatory to introduce but minimize redundant elements to ensure consistency with the space required, the complexity of the control system and the system maintainability. The most critical condition is expected when full 50 MW of EC power is required. Since for a power plant the operating time should be the highest possible to ensure the cost effectiveness, the Mean Time Between Failures (MTBF) must be as high as possible, where a fault is the impossibility to deliver to the plasma the required 50 MW. In this study it was assumed as acceptable value 1000 pulses for the MTBF, here defined in terms of pulses with 2 h length each. With this assumptions the operating time of at least 2000 h between two faults corresponding to 3 months of DEMO operations. The basic configuration is a system composed by l number of simple EC lines (ECL) made up of 1 Power Supply Unit (PSU), 1 gyrotron, 1 TL and 1 launcher. For each element a reliability R is assumed: gyrotron $R_G = 98$ %, launcher $R_L = 99{,}9$ %, TL $R_{TL} = 99{,}9$ % and $R_O = 100$ % for other components (once defined the real values the calculation will be updated). The reliability of a single ECL is defined [10] as the product of the single reliabilities $R_{ECL} = R_G R_L R_{TL} R_O$ and the reliability of the system is:

$$R_{System} = \sum_{i=k}^{l} \binom{l}{i} R^i (1-R)^{l-i}$$

where l is the number of necessary lines to deliver 50 MW to the plasma and $k = 28$ is minimum l considering 10 % of TL losses to compensate. The minimum number of ECL to reach the target of MTBF > 1000 pulses is $l = 32$ with a MTBF = 1595 pulses. This solution is conceptually simple but leads to an EC system with a very large number of TLs: the volume occupied cannot be overlooked in the design phase and maintenance can be very expensive or impossible. To reduce this number an alternative solution consists in a few clusters in which n gyrotrons and n launchers are connected by single MBTL including m gyrotrons and m launchers spares for the reliability, 1 PSU and n Power Switches (with R_{PS} assumed 100 %). The key component of the cluster configuration is the TL. In this case the total reliability of each cluster can be expressed [10] as:

$$R_{Cluster} = R_O \left(\sum_{i=n-m}^{n} \binom{n}{i} R_G^i (1-R_G)^{n-i} \right) * R_{TL} \left(\sum_{i=n-m}^{n} \binom{n}{i} R_L^i (1-R_L)^{n-i} \right)$$

Two options are viable: $m = 0$ cluster without backup components where the total reliability is improved increasing the number of clusters (as simple ECL configuration) and $m > 0$ cluster with backup component where the total reliability is enhanced by increasing the reliability of each cluster.

Table 3. Cluster configuration results of ECS reliability with 1 backup item.

Number of gyrotrons/ launchers per cluster [n+m]	Number of clusters [j] to deliver 50MW	R_{system} [%]	MTBF [pulses]	Total number of gyrotrons/ launchers
1+1	28+1	99,9601	2507	58
2+1	14+1	99,9896	9606	45
3+1	10+1	99,9945	18291	44
4+1	7+1	99,9972	35852	**40**
5+1	6+1	99,9979	47777	42
6+1	5+1	99,9985	66830	42
7+1	**4+1**	**99,9987**	**79870**	**40**
8+1	**4+1**	99,999	100198	45
9+1	**4+1**	99,999	100200	50

Table 3 shows the results for cluster with the use of one backup item (m=1). Two solutions with the minimum total number of 40 gyrotrons and launchers are possible: the first with n+m = 5 (4+1) and j = 8 (7+1) MBTLs, and the second with n+m = 8 (7+1) and j = 5 (4+1) MBTLs. The solution with j = 8 (7+1) is preferable because it results a good trade-off between a lower number of clusters (only 5) and a higher reliability and MTBF. The best solution is composed by only 5 MBTLs, each of them connected with 8 gyrotrons and 8 launchers (1 for both spare). Analogous result has been obtained with the analysis of $m = 0$ case. The cluster solution with $m = 1$ also reduces the number of subsystems, saves space with respect to the single ECL and the high MTBF assures safe margins when the real reliability of other single component (R_O) will be defined.

5 Conclusions

The DEMO EC system will be responsible for several key physical tasks but with much more limited flexibility compared to present experimental devices. Different options for gyrotrons, TLs and launchers are under evaluation taking into account the RAMI target requirement for a nuclear power plant. Multi-frequency

2MW gyrotron with high efficiency and reliability is the present source assumed. The study of RSA was approached whereas other simplified antenna types (e.g. TWG) will be considered at later stage. A preliminary calculation of blanket apertures has been conducted and the relative low impact on TBR evaluated and confirmed. The new concept of EQO MBTL can be a viable option for a DEMO reactor and adopted for system in cluster units as shown by analysis reaching the high required reliability. The details of EC system have still to be fixed but a design method in a reactor compatible way is progressing.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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