EUROfusion

WPHCD-CPR(17) 17203

AA Moro et al.

Conceptual design studies of the Electron Cyclotron launcher for DEMO reactor

Preprint of Paper to be submitted for publication in Proceeding of 22nd Radiofrequency Power in Plasmas Topical Conference (RFPPC 2017)

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.

Conceptual design studies of the Electron Cyclotron launcher for DEMO reactor

Alessandro Moro[1,*], *Alex* Bruschi[1], *Thomas* Franke[2,3], *Saul* Garavaglia[1], *Gustavo* Granucci[1], *Giovanni* Grossetti[4], *Kyriakos* Hizanidis[5], *Ioannis* Tigelis[6], *Minh-Quang* Tran[7], *Christos* Tsironis[5]

[1]Istituto di Fisica del Plasma, Consiglio Nazionale delle Ricerche, Milano, Italy
[2]EUROfusion Consortium, Boltzmannstr. 2, D-85748 Garching, Germany
[3]Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, D-85748 Garching, Germany
[4]IAM-AWP, Karlsruhe Institute of Technology (KIT), D-76131 Karlsruhe, Germany
[5]School of Electrical and Computer Engineering, NTUA, 157 73 Athens, Greece
[6]Faculty of Physics, NKUA, 157 84 Athens, Greece
[7]Swiss Plasma Center, EPFL, CH-1015 Lausanne, Switzerland

Abstract. A demonstration fusion power plant (DEMO) producing electricity for the grid at the level of a few hundred Megawatts is included in the European Roadmap [1]. The engineering design and R&D for the electron cyclotron (EC), ion cyclotron and neutral beam systems for the DEMO reactor is being performed by Work Package Heating and Current Drive (WPHCD) in the framework of EUROfusion Consortium activities. The EC target power to the plasma is about 50 MW, in which the required power for NTM control and burn control is included. EC launcher conceptual design studies are here presented, showing how the main design drivers of the system have been taken into account (physics requirements, reactor relevant operations, issues related to its integration as in-vessel components). Different options for the antenna are studied in a parameters space including a selection of frequencies, injection angles and launch points to get the best performances for the antenna configuration, using beam tracing calculations to evaluate plasma accessibility and deposited power. This conceptual design studies comes up with the identification of possible limits, constraints and critical issues, essential in the selection process of launcher setup solution.

1 Introduction

The design of a DEMOnstration Fusion Power Plant includes heating systems as mandatory to achieve controlled burning plasma and reactor relevant conditions. In the framework of EUROfusion Consortium activities, the Work Package Heating and Current Drive (WPHCD) is performing the engineering design and R&D for the Electron Cyclotron (EC) [2, 3], Ion Cyclotron (IC) and Neutral Beam (NB) systems for the DEMO reactor. In the present stage of DEMO design, the EC target power to the plasma is 50 MW. This power, when confirmed by detailed scenarios simulation, must be assured during the entire DEMO pulse length. The different EC tasks foreseen in DEMO [4] (listed in Table 1) require different deposition locations in the plasma (from $\rho < 0.3$ up to $\rho = 0.86$, being ρ the normalized plasma radius) and a defined amount of power. A launcher with a good degree of flexibility and compatible with the main technical constraints is also required. In order to cover all the EC applications a candidate option for DEMO launcher could be based on Remote Steering Antennas (RSA), able to grant a continuous (but limited) steering range with no movable parts or mirrors in plasma proximity. As an alternative, simpler truncated-waveguide antennas can also be considered, in combination with step-tunable gyrotrons presently under development [5].

The status of a conceptual design study for an EC launcher is here presented, with evaluation of possible antenna options and potentials for multi frequency gyrotrons, launching performance, plasma accessibility, possible integration into port plug and preliminary evaluation of required apertures for antenna assembly.

Table 1. DEMO EC tasks and operation modes with corresponding required power and deposition location in terms of normalized radius.

EC Task	Mode	Power [MW]	Deposition [ρ]
Assisted Breakdown	Heating	6-10	<0.3
Ramp up and L-H transition	Heating/CD	50	<0.3
Heating	Heating/CD	50	<0.3
Sawtooth control	CD	2-10	<0.3
NTM control (q=2;q=3/2)	CD	10-15	0.86; 0.76
Ramp down	Heating	40	[0.3-0.5]

2 EC Launcher configuration definition

The conceptual design study presented here relies on the EU DEMO1 2015 baseline for a pulsed machine with aspect ratio AR = 3.1 and B_T = 5.7 T [4]. The EC system is configured with high modularity and organized in clusters (with 8x2 MW gyrotron per cluster) [6]. The 8 EC beams of a cluster delivers to a single plug-in launcher composed by 8 independent antennas per port. An exception under study is considered for the gyrotrons dedicated to NTM control that would use two different launchers (4 beams each) located in two different ports. The total number of cluster considered is 4+1 for main EC tasks and one for NTM stabilization.

* Corresponding author: moro@ifp.cnr.it

A selection of candidates fixed launching points, corresponding to waveguide termination locations have been identified (see points coordinates in Table 2.1), taking into account locations distributed in the equatorial port plug and in the larger major radius region of the vertical port plug (that could also be considered as hypothetical terminations for an upper port at ITER). To simulate EC injection in a wide range of possible configurations the parameters for beam tracing calculations have been chosen variable in steps, in angular and frequency ranges (square brackets) listed in Table 2.1. Wave frequency range includes 170 GHz, seeking compatibility with the EC system of ITER, for heating, 204 GHz for current drive tasks and discrete frequencies for heating and current drive operations in line with multi-frequency (e.g. 136/170/204/238GHz) or step-tunable gyrotron sources presently under development [5]. Even if the final choice will be done when the EU DEMO conceptual design phase will be completed, the selected range for this study focuses on 170 GHz and 200 GHz.

Table 2. Selected parameters space for beam tracing calculations.

Parameter		Value/Range
EC wave frequency	f	[140 GHz -240 GHz]
Beam waist	w_0	20.43 mm
Equatorial launch points {X,Y,Z} [m]	EPP_i	EPP_3={13.5, 0, 0}, $EPP_{1,2}$={13.5, 0, ±0.67}
Vertical/Upper launch points {X,Y,Z} [m]	UPP_i	UPP_1={12.2, 0, 4.2}, UPP_2={10.7, 0, 3.9}
Toroidal angle	β	[0°,40°] for EPP_i
Poloidal angle	α	[-30°, 30°] for EPP_i [0°, 50°] for UPP_i

The analysis was done with the beam tracing code TORBEAM [7] and a self consistent plasma scenario for DEMO1 obtained with ASTRA [8] code. TORBEAM runs provide the resulting beam trajectories, from which numerical parameters including the deposition location ρ of EC power absorption, the current drive efficiency η, the absorbed power P_{ABS}, the total driven current I_{CD} and the deposition profile width $\Delta\rho$ as function of frequency f and injection angles α □□□ β, organised in a multi-dimensional matrix.

3 Remote Steering Antenna (RSA) option

The selection of favourable launching configurations requires the identification of an antenna axis and a steering plane capable to cover the widest range of deposition locations, corresponding to the required tasks, and, for NTM stabilization, with a sufficient amount of driven current up to ρ □ 0.86. A candidate option for DEMO EC launcher conceptual design is the RSA. A maximum steering range $\Delta\gamma$= ±15° is studied, centered at a nominal injection direction given by the angles β_0, α_0 and the steering plane is defined by the angle θ of its normal versor with respect to a horizontal direction (as shown in Fig. 1). The pair of poloidal and toroidal are expressed in terms of the cylindrical components of the wave vector **k** as follows: k_R=cosαcosβ, k_ϕ=sinβ, k_z=−cosαsinβ to give tanα=k_z/k_R and sinβ=k_ϕ. Results in terms of deposition location accessibility ρ (normalized plasma radius) and driven current I_{CD} are mapped in Fig. 2 as a function of the two angles α and β, for a beam at two frequencies (170 GHz top, 200 GHz bottom) and waist at the launching position w_0=20.4 mm) launched from an equatorial port plug point (EPP_3). The toroidal and poloidal injection angles in the maps vary in the range β=[0°, 30°] and α=[-30°, 30°], respectively.

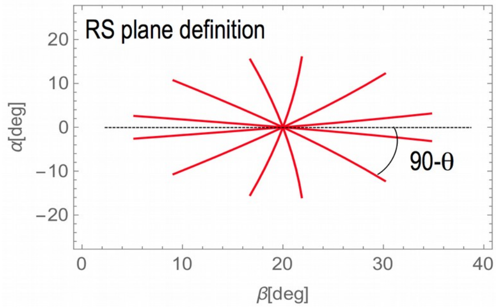

Fig. 1. Examples of possible launching angles pairs α and β, when steering is performed ($\Delta\gamma$= ±15°), centered on pair of anglesβ□20°, α□̃°. Each curve corresponds to a given steering plane orientation.

Widest coverage of plasma regions is found for steering planes orthogonal to the iso-radius curves, although this is not straightforwardly accompanied with high values of total driven current, which are strongly frequency-dependent.

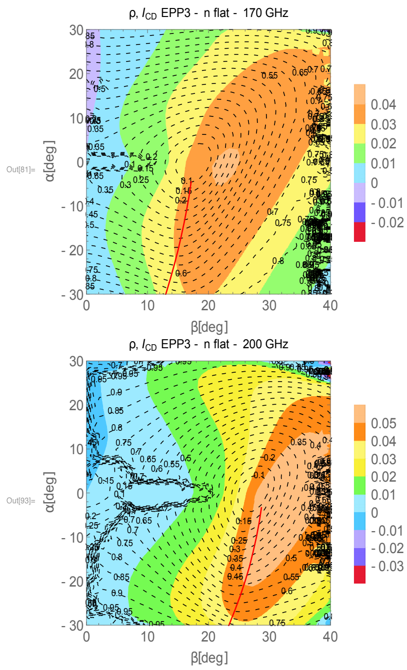

Fig. 2. Contour plots for normalized deposition location ρ (black dashed curves) and total driven current I_{CD} (color code, MA/MW) as a function of the injection angles (α, β) with different possible steering planes (red lines) in the parameters space. The cases of 170 GHz frequency (Top) and 200 GHz (bottom) are shown.

A given steering plane, proved to be good for one frequency, is not suitable for higher (or lower) frequencies, as show in Fig 3, where the total amount of driven current I_{CD} is plotted as a function of ρ (along one specific steering plane) in the case of 170 GHz and 200 GHz. A steering plane with parameters β_0=15°, α_0 =-20°, θ=-5° ensures that only 170 GHz EC beams covers large plasma regions (red curve in Fig. 3 left) when compared to the 200 GHz case. The opposite situation is found with steering plane parameters β_0=26°, α_0=-20°, θ=-5° promising at the higher frequency better plasma coverage and total driven current compared to the 170 GHz case with same orientation (Fig. 3 right).

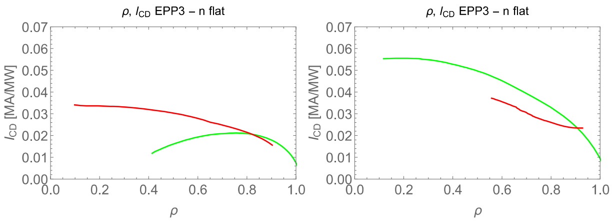

Fig. 3. Normalized total driven current I_{CD} as a function of accessible deposition location ρ with the beam launched from EPP3 with steering plane parameters β_0=15°, α_0=-20°, θ=-5° (left) for 170 GHz (red) and β_0=26°, α_0 =-20°, θ=-5° (right) for 200 GHz (green).

A comparison of the current drive efficiency η for the two optimal cases is shown in Fig. 4, where it appears that highest frequencies are more efficient for inner deposition, while at outer locations the difference is not so appreciable.

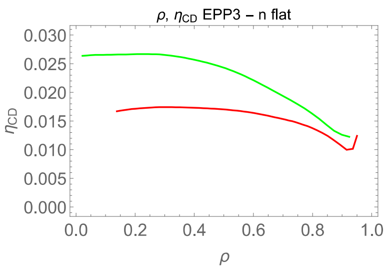

Fig. 4. Calculated current drive efficiency along the steering planes as a function of deposition location. Higher efficiency along the range is found for 200 GHz (green curve) with respect to 170 GHz (red curve).

The study of the overall performance of a given configuration cannot neglect to consider also the deposition profile width that characterises the EC absorption. It is modelled assuming that it is close to a gaussian, with most of the power released at a deposition location $\rho \pm \Delta\rho/2$, being $\Delta\rho$ defined as the full current density profile width at *1/e* of the peak value. Smaller deposition profile widths are beneficial of course, in particular for EC applications requiring current density with narrow profile as in the case of NTM control, where deposition within the magnetic island is mandatory for mode stabilization. In the cases considered, the total driven current around the q=2 location (ρ = 0.86) is I_{CD} = 25.3 kA/MW with $\Delta\rho$ = 0.06 in the case of 170 GHz, I_{CD} = 27.6 kA/MW, $\Delta\rho$ = 0.14 in the case of 200 GHz. The expected lower deposition profile width with reduced length of the beam path from launcher to EC absorption region, motivated the analysis of a launching point from a higher position with respect to the equatorial port. The outcome is reported in Fig. 5, which shows the contour map of the total driven current obtained with UPP_1 launch, considering promising steering planes for 170 GHz and 200 GHz. In these cases smallest $\Delta\rho$ are found at 200 GHz, with $\Delta\rho$<0.03. It has to be pointed out that even if larger amount of driven current are achievable at larger toroidal angles (β>30° in 200 GHz case), these angles have the drawback to give even larger deposition profile width $\Delta\rho$, so toroidal injection in the range 15°<β<30° seems a better trade-off.

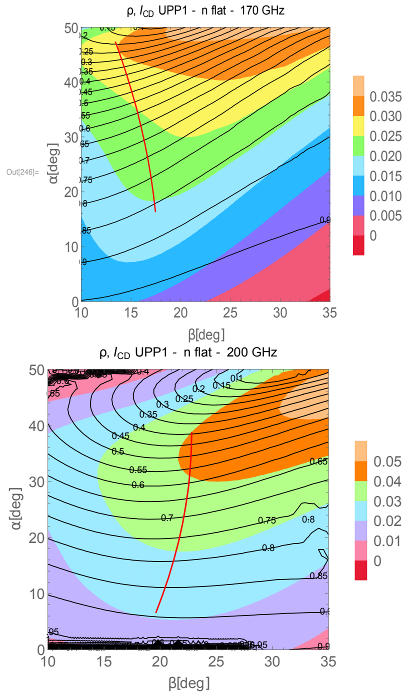

Fig. 5. Contour plots for normalized deposition location ρ (black dashed curves) and total driven current I_{CD} (color code, MA/MW) as a function of the injection angles (α, β) with different possible steering planes (red lines) in the parameters space. The cases of 170 GHz frequency (top) and 200 GHz (bottom) are shown.

A comparison similar to the EPP_3 shows that 200 GHz ensures higher values of I_{CD} with reduced plasma region accessibility (Fig 6). The lower frequency has a slightly wider range of accessible locations with lower efficiency.

As a general result of the conceptual studies done so far on the RSA it could be a valid option for inner EC tasks in terms of deposition location in the plasma, where large steering required to cover regions ranging from ρ < 0.2 up to ρ □ 0.5, and operating at one frequency (~200 GHz). For NTMs control the simpler truncated waveguide will be investigated as an alternative, to be used at fixed orientation and exploiting the multi-frequency and step tunability of the sources under development for the fine-tuning of the deposition.

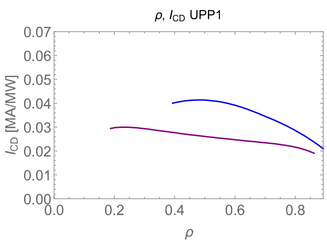

Fig. 6. Normalized total driven current I_{CD} as a function of accessible deposition location ρ with the beam launched from UPP_1. The steering plane parameters are β_0=16°, α_0=32°, θ=-2° for 170 GHz (purple) and β_0=22°, α_0=22.5°, θ=-15° for 200 GHz (blue).

4 Port integration studies

The RSA option has limits that must be taken into account for launcher integration since the early stage of a conceptual design [9]. In particular, good beam characteristics can be obtained for a limited angular range (10°-15°) [10] centered on the waveguide axis and this range affects the width of the required apertures on the blanket modules. Preliminary estimation of a group of 8 waveguides packed in a row and providing a steering in the poloidal direction requires an aperture at blanket level A=0.19 m^2 (~0.5 m^2 for the whole pack and ~2.5m^2 considering five ports). The waveguide length in a RS arrangement is of the order of several meters and increases with frequency. In the case of a waveguide aperture a=75 mm and f=204 GHz the required length is $L_{RS}\cong$15 m. Moreover, the waveguide routing within the plug towards ex-vessel DEMO environment must be compliant with the constraint that mitre bends can be inserted only in positions not too close to the waveguide (WG) termination, with bends and doglegs allowed only in the plane perpendicular to the chosen steering plane. An example of a possible setup showing blanket apertures and waveguide routing is sketched in Fig. 7, where a top view of the arrangement (left) and a front view of the waveguide apertures to allow beam steering (right) are presented, in case of a single row arrangement for the 8 waguides with central injection at port aperture.

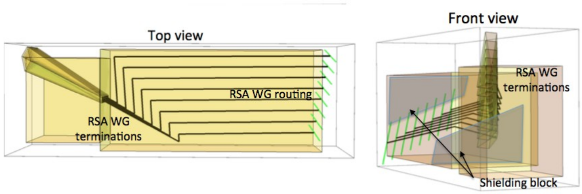

Fig. 7. Left: Sketched top view of a possible RSA pack assembly with a single vertical row of eight antennas toroidally inclined in an equatorial DEMO port. Right: RSA pack as viewed from the plasma, with gray regions representing volumes available for neutron shielding blocks.

Alternative configurations could also be considered, with different waveguide arrangements (for example using 2 rows per port, and side injection at port aperture, as shown in Fig. 8). Any configuration has to be evaluated in terms of neutronics issues, mechanical impact on breeding blanket, tritium breeding ratio, bioshield interactions and interfaces. An evaluation of the impact of apertures of the EC launchers in terms of tritium breeding ratio degradation has been performed starting from similar antenna design [11].

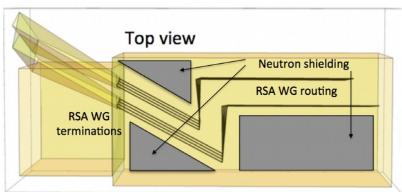

Fig. 8. Sketched top view of a possible RSA pack assembly with 2 vertical rows of four antennas toroidally inclined in an equatorial DEMO port. Gray regions represent volumes available for neutron shielding blocks.

5 Conclusions

Guidelines for a conceptual design of an EC launcher for DEMO reactor were presented in this paper with preliminary illustration of an antenna design, that aims at fulfilling the requirements with efficient and reliable EC deposition. The choice of the preferred antenna solution (steering plane orientation in the case of RSA or combined RSA and truncated waveguides properly oriented) should be validated through more detailed beam tracing calculations presently ongoing (in order to evaluate in a quantitatively way the performances in terms of EC injection and deposition) and through port plug integration feasibility study with an iterative approach to adapt the solution to engineering and physics requirements.

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.

References

1. F. Romanelli et al., https://www.euro-fusion.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf
2. S. Garavaglia et al., AIP Conference Proceedings **1689**, 090009 (2015)
3. G. Federici et al., Fusion Eng, and Design **109-111**, Pages 1464-1474 (2016)
4. R. Wenninger et al., Nucl. Fusion **57** (2017) 016011
5. J. Franck et al, IEEE International Vacuum Electronics Conference (2014) 31-32R
6. S. Garavaglia et al., Proc. of EC19EPJ, Web of Conferences, accepted for publication (2017)
7. E. Poli et al., Comput. Phys. Comm. 136, 90 (2001)
8. G.V. Pereverzev, P.N. Yushmanov, IPP-Report 5/98, (2002)
9. G. Grossetti et al. Proc. of 26th FEC – Kyoto (2016) FIP/P7-4
10. W. Kasparek et al., EPJ Web of Conferences **87**, 0-4-00 5 (2015)
11. G. Granucci et al., Submitted for publication in Nucl. Fusion