ECRH and ECCD modeling studies for DEMO

B. Baiocchi[1], A. Bruschi[1], L. Figini[1], S. Garavaglia[1], G. Granucci[1], A. Moro[1]

[1] Institute for Plasma Science and Technology - CNR, via Cozzi 53, 20125 Milano, Italy

Introduction

The electron cyclotron (EC) system foreseen for DEMO has the aim of achieving several physics tasks, in the first phases, during the flat top period and at the end of the plasma discharge: assisted plasma break-down and start-up, current ramp-up, bulk heating (BH) of core plasma, MHD (NTM) control, radiative instability (RI) control and current ramp-down. Then the EC system must provide proper different radial localizations and combination of heating and non-inductive current drive (CD), taking into account the peculiar physics requirements and the engineering constraints of a fusion power plant reactor. The investigation and the optimization study of the performances and the limits of the EC launcher is then essential for the accomplishment of the tasks in the context of the reliability of DEMO EC system [1]. In order to select optimized launcher configuration, the beam tracing code GRAY [2] has been used, performing scans in the launcher parameters space defined by the injection angles, the wave frequency and the antenna position. Such study has been applied to the flat top phase of the DEMO1 scenario [3], using as input for GRAY the physics baseline (BL2018) of DEMO1 [4], characterized by B_t=6 T, Ip=18 MA (with plasma current (I_p) with clockwise direction looking at the tokamak from the top, co-directed to the toroidal magnetic field (B_t)), and by the kinetic profiles reported in fig. 1a. Fig. 1b shows some baseline scenario equilibrium features (the poloidal projection of the flux surfaces, with rational surfaces in green) and the launcher parameters, i.e. the resonance layers in the plasma correspondent to the 2 selected frequencies of the EC launcher for DEMO1, and examples of the beams paths launched from the Equatorial Port (EP) launcher positions.

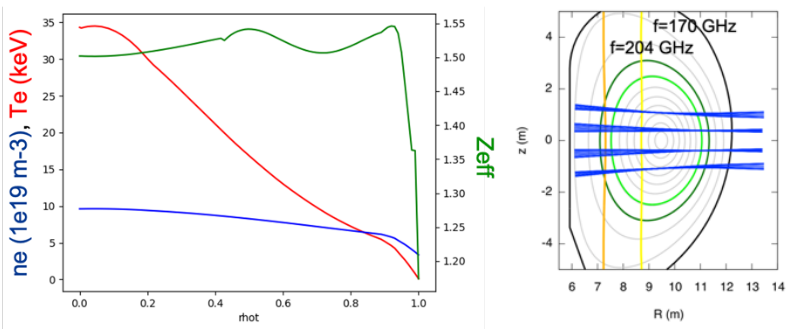

fig. 1: (left) ne, Te and Zeff profiles of the baseline DEMO1 scenario, used as input in beam tracing simulations. (right) path poloidal projection of different EC beams varying the launching position (with null poloidal and toroidal angles). In orange (yellow) the resonance layer for 204 (170) GHz. In (dark) green the poloidal projection of q = 3/2 (2) surfaces.

1) Bulk Heating

In order to launch and deposit nearly 30 MW for plasma BH, the EC system is foreseen to be equipped by 2 modules in the central part of the EP (Multi-Beams Mirror launchers) with 8 beams per module (see fig. 1b and [1]). The optimization study of the BH launcher is focused on the localization and the absorption efficiency of the deposited power. Ray tracing simulations are performed varying the launching poloidal (α) and toroidal (β) angles at the selected frequencies of 170 GHz and 204 GHz and intervals of angles are extracted fixing as constraints central power absorption (i.e. the percentual of the absorbed power inside the radial coordinate ρ=0.3 ($P_{abs,\rho<0.3}$) > 85%) and centrally localized deposition (i.e. average power deposition location ($\rho_{dep,av}$) < 0.25) for both frequencies. Poloidal angles in the interval of 0-10 deg and toroidal angles in 20-25 deg are found to satisfy such requirements. Fig. 2 shows the power density deposition profiles at the two launching frequencies for 3 couples of angles belonging to the selected intervals. The couple α=5 deg, β=21 deg is considered as optimal because it gives central deposition for both frequencies. This analysis refers to one representative beam of the upper equatorial mirror. The same study is performed for the lower mirror and equivalent results are found. Starting from the chosen couple of angles, optimized angles couples are calculated for the other beams, taking into account the real launcher modules geometry. Fig. 3 shows the resultant power density deposition profiles for all the beams. For both frequencies the centrality of the deposition and the absorption is assured.

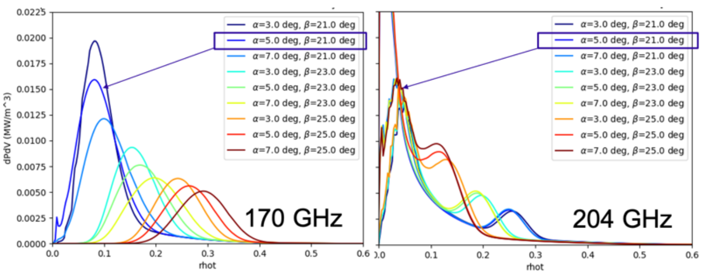

fig. 2: calculated power density profiles at 170 GHz (left) and 204 GHz (right) of 1 beam (B8 [5]) of the upper equatorial mirror, with a choice of three representative cases of the intervals α=[0,10] deg and β=[20,25] deg (lower mirror gives the same results).

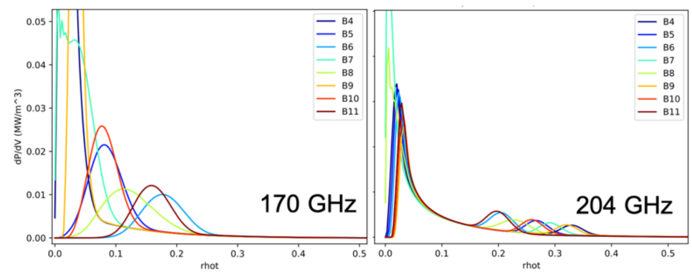

fig. 3: calculated power density profiles at 170 GHz (left) and 204 GHz (right) of the beams of the upper BH module (from B4 to B11 [5]) with calculated α and β starting from the choice done for B8.

2) NTM mitigation

The launching antennas for NTM mitigation are 2 modules (Middle-Steering Antennas), placed in the top and bottom part of the EP, with 3 beams per module. To the NTM mitigation aim the main requirements concern a good deposition localization, a sufficient total current value and enough narrow current density width (i.e. the average current density deposition width $\Delta\rho_J$ < 0.02). Ray tracing simulations are performed varying poloidal and toroidal angles at 170 GHz with the constraints of co-directed driven current with respect to the plasma current, and of accessing both rational surfaces (in correspondence of the q values of 3/2 and 2), i.e. the flux surfaces where the NTM instabilities may rise. Fig. 4 shows the driven current per unit of injected power with varying α and β, for the central beams of the top and bottom antennas: β>0 gives co-driven current, from the top (bottom) module both rational surfaces are achieved by negative (positive) α. The intervals of optimal angles have been further reduced considering as additional requirement a minimum driven current per unit of injected power ($|I_{cd}/P_0|>5$ kA/MW). Beam tracing simulations are performed, and optimized angles couples are selected obtaining the best compromise between enough high driven current and narrow current deposition width.

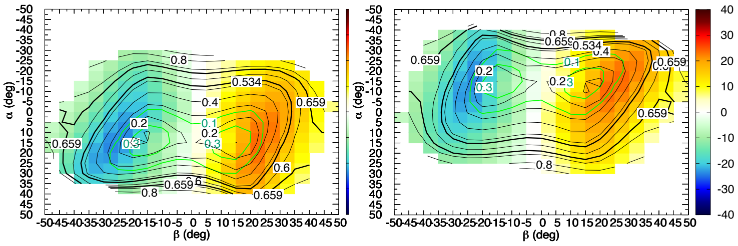

fig. 4: calculated driven current per unit power injected at 170 GHz for the central beams of the top (left) and bottom (right) NTM mirrors with varying poloidal (α) and toroidal angles (β). Driven current average location is represented by thinner black contours. Location of the rational q surfaces (ρ=0.534 for q=3/2 and ρ=0.659 for q=2) are shown by bold black lines. Green lines represent the fraction of the absorbed power at 2nd harmonics.

Excluding the large angles setups, which have the drawback to get closer to operational limits, the deposition on q=3/2 (2) is optimized using the top (bottom) module with optimal angles couple α=-15.2 deg, β=25 deg (α=23.15 deg and β =16 deg). Fig. 5 shows the values of the driven current and the current deposition width as functions of the radial coordinate, varying α and β.

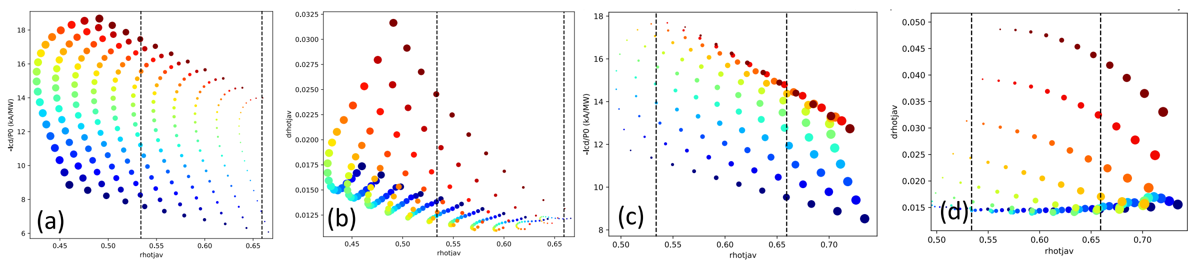

fig. 5: driven current per unit power injected at 170 GHz (a,c) and relative current deposition width (b,d) for (a,b) top module (B2 [5]), (c,d) bottom module (B21 [5]: different colours refer to different β values (cold (hot) colours for lower (higher) β), the marker dimension refer to the α value (small (large) circle for lower (higher) α). Dashed lines refer to q=3/2 and q=2 surfaces.

The last optimization step is done by focalizing the beam in correspondence of the maximum absorption point. Keeping fixed the dimensions of the beam at the mirror, the front phase curvature, and then the mirror focal length are varied. The optimal focalization value in the location of the maximum power absorption of the beam is chosen. The following values have been obtained: for q=3/2 I_{cd}/P_0=-15 kA/MW, $\Delta\rho_J$=0.009 for q=2 I_{cd}/P_0=-14 kA/MW, $\Delta\rho_J$=0.009. Adapting the selected couples for the other beams of the NTM modules and taking into account design considerations and constraints,

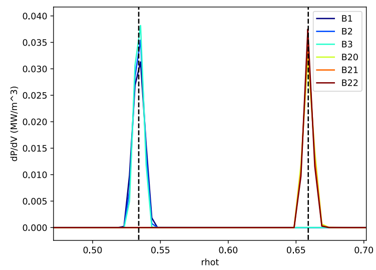

fig. 6: calculated power density profile at 170 GHz for the beams of the top and bottom NTM module (B1-B3, B20-B22 [5]) with calculated poloidal and toroidal angles based on the study for the top and bottom single beams B2 and B21.

enough narrow and very well localized beams can be obtained for all the NTM modules (see fig. 6).

3) Preliminary study of EC edge deposition for RI mitigation

In order to accomplish the task of depositing a relevant amount of power (~70 MW) in the edge plasma region, present, modified and hypothetical launcher configurations are considered. For present launchers the power can be delivered in the edge region only opportunely varying the injection frequency. For the BH launcher the edge region is achieved with frequencies lower than 170 GHz (see fig. 7). The NTM launcher with the launching angles in a narrow range as designed in 2019 can deposit power in the plasma edge with a frequency in the following intervals: 115-120 GHz, 132-134 GHz, 220-230 GHz and for frequencies > 240 GHz. These are very narrow intervals, dependent on the plasma parameters, that lead to critical correct deposition. If modifications of present launchers, allowing variation in the launching angles, are considered, the edge deposition is achieved by BH launcher varying β only in the frequency interval of 100-140 GHz. The NTM launcher can deposit in the edge region at 170 GHz by changing the poloidal angle α. Among the alternative launching locations, hypothetical "oblique upper" and "purely equatorial plane" launchers are considered. From specific locations the beams can achieve the edge region with lower path, minimizing the effects of refraction and turbulence. An upper launcher could give a better controlled and narrower edge deposition at 170 GHz while a horizontal launch in the equatorial plane could minimize the power deposition broadening due to finite beam size.

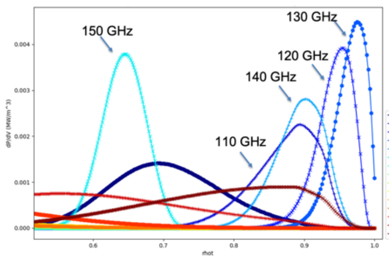

fig. 7: power deposition of a single beam of present BH launcher for different frequencies (outer plasma region).

Conclusions

Modelling of DEMO EC launch performances has been used for updating and confirming the launchers' design. For the BH task the injection angles are selected as reference orientations for specific beamlines and central deposition on the plasma is obtained for both frequencies 170 GHz and 204 GHz. Regarding the NTM mitigation task the optimization is achieved for both rational surfaces using 2 different modules at 170 GHz: narrow localized deposition profiles are obtained. Finally, the preliminary study about the RI mitigation task indicates BH modules as preferable candidate to achieve the plasma edge with modified lower frequency (130-140 GHz) (136 GHz is compatible with the 170-204 GHz window).

References: [1] T. Franke et al., FED 168,112653 (2021) [2] D. Farina, Fusion Science &Technology 52, 154 (2007) [3] Wenninger R. et al, Nucl. Fusion 57 016011 (2017) [4] EU DEMO baseline version February 2018 (2NLP3X) [5] report EFDA_D_2NQWKD and references in there. **Acknowledgment**: *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 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.*