An analysis of the physics requirements for scenario control for the ECRF system of JT-60SA

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Introduction

JT-60SA is the large superconducting tokamak, due to start operation in 2020, being built under the Broader Approach agreement jointly by Japan and Europe[1]. It is designed to address many areas of fusion science in preparation of the burning plasma era of ITER and DEMO, in particular the ones related with the control of high β steady state plasmas and the confinement of high energy particles. A key tool in the machine will be the 7 MW, 9 gyrotrons ECRF system which, as for the 34 MW NBI system, will be available in the Integrated Research Phase. Up to 3 MW of ECRF power will be available in the Initial Research Phase after a staged commissioning. The ECRF system will support several applications as assisted start-up and EC wall conditioning for which 82 GHz, ~1s gyrotron operation is being developed, bulk heating and current drive, magneto-hydrodynamic instabilities control for which gyrotron operation at full power and pulse length (100s) at 110 GHz and 138 GHz is being developed [2]. In order to allow the needed flexibility the ECRF system will operate over an extended range of injection angles: nominally toroidal $-5° \leq \beta \leq 25°$ and poloidal $-20° \leq \alpha \leq +40°$. The 9 gyrotron beams will be delivered to 4 antenna systems in 4 toroidal sectors, 3 of which with 2 beams with a small toroidal shift, and 1 with 3 beams. This last will have a more limited steering range. The ECRF antenna design has been driven by the need of reliability for long pulse operation and wide flexibility in the applications [3]. The optical efficiency has been optimized within such constraints. In particular, most of the moving components are remote from plasma. Being the ECRF beams entering the plasma astigmatic and divergent the power density is significantly variable along the beam path. The accurate evaluation of the EC power and current (densities) achievable along the minor radius requires the detailed analysis of the beams at the antenna exit keeping into account the details of the launching configurations and including the main geometrical constraints. For such purpose the far field antenna patterns have been computed with the Physical Optics tool GRASP® [4] and then fitted with astigmatic Gaussian beams (first sidelobes at -25dB) to feed the GRAY code [5] for the heating and current drive analysis.

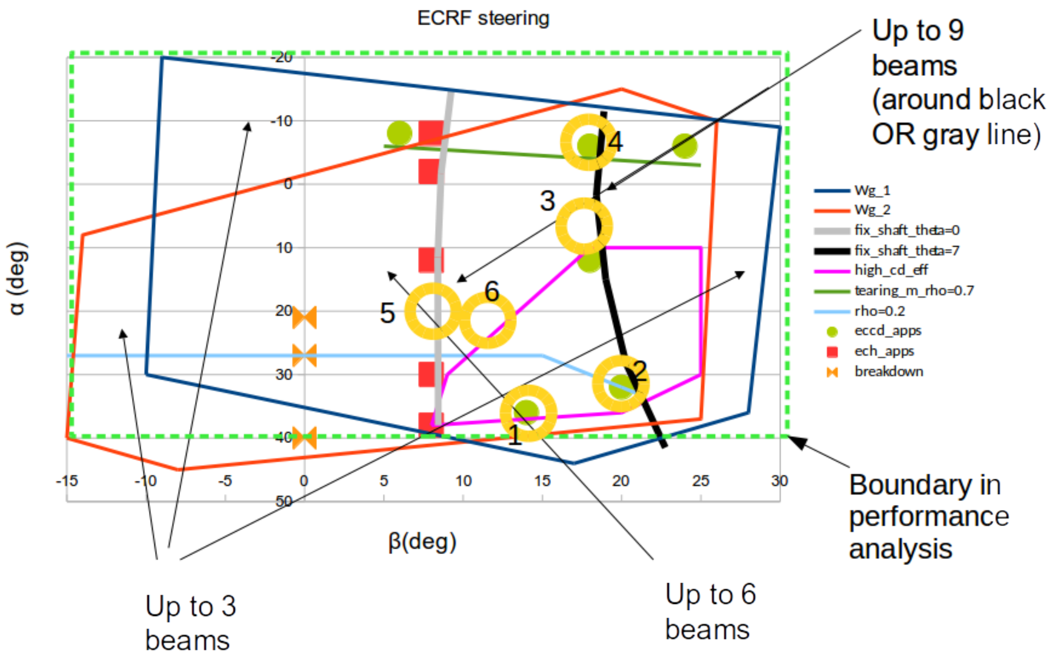

Figure 1 Operational diagram for ECRF applications in the available steering range (see text)

ECCD for scenario control

Figure 1 represent the operational diagram of the ECRF antenna systems keeping into account the main geometrical constraints, such the left/right asymmetry of the achievable angles for each beam marked by the blue and orange contours respectively, and the limited steering range of the 3-beams antenna. For this last the assumption taken here is that only one given toroidal angle is selected. Two possible options are shown, with poloidal steering along the grey line to favour ECH applications or alternatively along the black line in order to favour ECCD applications. The results of such analysis are used in this paper to assess in particular the current drive capabilities of the ECRF system in order to contribute to the control of the operational scenarios under development [6], which include the full-I_p inductive H-mode scenario (#2, B_t~2.25 T, Ip=5.5 MA, q_{95}~3, n_e/n_{GW}=0.5, β_N=3.1), the advanced ITER-like inductive scenario (#4.2, B_t~2.3 T, I_p=3.5 MA, q_{95}~4.4, n_e/n_{GW}=0.8, β_N=3) and the steady state scenario (#5.1, B_t~1.7 T, I_p=2.3 MA, q_{95}~5.8, n_e/n_{GW}=0.85, β_N=4.3). Use of ECRF mainly at 138 GHz, X2 mode is foreseen for scenarios #2 and #4, while 110 GHz, X2 for scenarios #5. As shown in figure 2, a driven current up to 15-40 kA/MW is achieved depending on the scenario. A clearly defined region of effective current drive (10<β<25 10<α<40, corresponding to ρ_t<0.4) can be identified in scenario #2 and particularly in scenario #4-2. In scenario #5-1 the X2 resonance is in the high field side and the accessibility is restricted to ρ_t>0.4. Analysis at the frequency corresponding to 3rd harmonics shows a broad, parasitic absorption in the low field side close to the edge region.

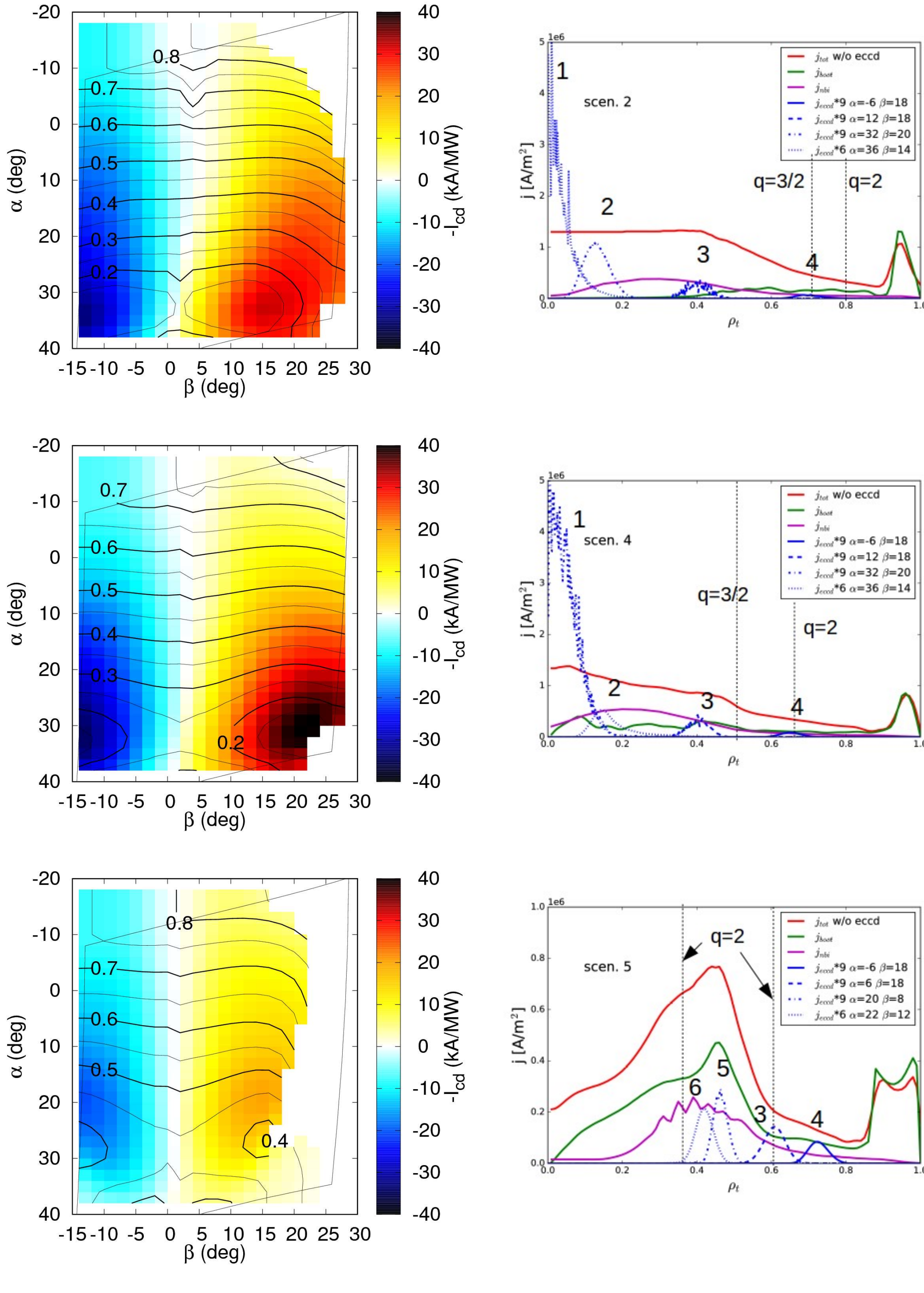

Figure 2. Left column: current drive maps along the steering range for scenarios #2 (top), #4-2 (mid), #5-1 (bottom). Black contours are the flux surfaces in ρ_t. Right column: current density profiles. ECCD current density profiles at different radii are computed with the maximum number of gyrotron sources available at that value of the minor radius according with figure 1, which is also given in the plot labels. Numbers close to the j_{eccd} profiles mark the corresponding launch settings of figure 1.

The ECCD driven current density is strongly varying along the radial coordinate, due to both the volume effect at increasing minor radius and to the beam divergence as the distance from the antenna increases. As it is shown in the left column of figure 2, the ECCD term is the dominant current drive contribution in the core in scenarios #2 and #4-2. In those plots the total current density j_{tot} is plotted without the j_{eccd} contribution. The comparison with the bootstrap term in scenarios #2 show that $j_{eccd}< j_{boot}$ in the region where q=3/2 and q=2 NTM are expected, marked with the dashed vertical lines. In scenarios #4-2 and #5-1 instead $j_{eccd}\sim j_{boot}$. In all the cases it is assumed the use of all the available power for NTM control. The actual ECRF power and j_{eccd} requirements for NTM control are being evaluated using the Generalized Rutherford Equation keeping into account the performance analysis here summarized.

Since reduced magnetic field and plasma current operations might be considered in the starting phase of JT-60SA in order to commission the scenarios, a preliminary evaluation of the absorption in such conditions has been performed. A scaled down H-mode scenario at constant B/I_p, n_e/B, T_e/B based on nominal #2 has been considered. The ECRF absorption at the third harmonics remains relatively high for a reduction up to of 60% of the nominal field, with accessibility $\rho_t>0.3$ for 138 GHz and $\rho_t>0.15$ for 110 GHz.

Other ECRF functionalities essential to initiate JT-60SA operations are being considered as EC wall conditioning [7] and EC assisted breakdown. Those will imply the launch of multi MW power in presence of very low single pass absorption. An EC-stray detection and protection system with the purpose of enabling safe operations in such conditions is under study [8].

References

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