Design and optimization of a curved three-strap antenna for DTT ICRH system

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Abstract. The Divertor Tokamak Test facility (DTT) aims at demonstrating possible solutions to the power exhaust issue to pave the path to DEMO. Here we present the numerical design and optimization of a three-strap Ion Cyclotron Resonance Heating (ICRH) antenna suitable to deliver Ion Cyclotron Radio Frequency (RF) Power on DTT plasmas. The launcher operates in the frequency range 60 – 90 MHz and here has been studied and optimized by using the commercial RF simulation software CST Studio Suite. The plasma is considered as an equivalent, high permittivity, lossy dielectric. Considering the mechanical and operational severe constraints of DTT, we firstly designed an antenna flat model with the objectives to optimize the structure for coupling a power ≥ 1.5 MW to the dielectric load with a progressive phase shift of 180° between toroidally adjacent straps. The second part of the work regarded the design and optimization of a parametric curved antenna model in CST, which employs poloidal and toroidal curvatures suitable to better couple RF to DTT plasmas. The antenna curved model has been re-optimized in terms of coupled power and electric field values to match DTT requirements.

1 Introduction

The Italian Divertor Tokamak Test (DTT) facility is conceived to allow various magnetic configurations and reproduce edge conditions close to DEMO for a reactor-relevant exploration of alternative power exhaust solutions in an integrated scenario [1], as envisaged in the European roadmap to fusion electricity. To attain a power-over-radius ratio of around 15 MW/m crossing the separatrix, a heating power of 40 – 45 MW is required and will be provided by a suitable mix of electron cyclotron resonance heating (ECRH), neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH) waves. Because of DTT scenario flexibility, the coupling of waves at the ICRH frequencies is a difficult task. Moreover, the reliability of auxiliary heating systems is a primary target in DTT design, thus imposing sound solution in RF coupling structures. This determines a step approach strategy in defining the ICRH system. Indeed, an initial step of limited power will demonstrate the handling capability of the chosen antenna that must guarantee a power of 1.5 MW delivered to the plasma, keeping the electric fields $|E| \leq 2.5$ MV/m and $|E_{\parallel}| \leq 1.5$ MV/m in the antenna and minimising spurious fields responsible for ion sputtering. Moreover, to avoid possible electrical breakdown phenomena, the maximum allowable voltage in the four coaxial cables, $V_{standoff}$, has been fixed to a conservative value of 35 kV. The so-called day-1 additional power configuration will be composed by 1 NBI injector (10 MW at plasma), 2 ICRH antennas (1.5 MW of coupled power each antenna) and 2 ECRH clusters (8 MW installed from 8 gyrotrons at 170 GHz for each cluster).

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2 ICRH 3-strap antenna design

DTT ICRH system [2] works in the frequency range 60 – 90 MHz, whose extreme frequencies locate the cyclotron resonances of ^{3}He and H minorities, respectively, at the DTT magnetic axis in the reference 6 T scenarios [3–5]. The system can also support electron heating via mode conversion and wall conditioning through 2nd harmonic cyclotron heating of majority D ions. Figure 1 shows the spatial profiles of the cyclotron frequencies $\Omega_{c\,^3\mathrm{He}}(\hat{x})$ and $\Omega_{c\,\mathrm{D}}(\hat{x})$ for ^{3}He (blue) and deuterium (orange) ions, computed along the normalized radial coordinate $\hat{x}$ in a specific DTT minority heating scenario (when $\hat{x} = 1$ we are close to the antenna). Both frequencies decrease monotonically toward the plasma edge due to the reduction of the magnetic field $B(\hat{x})$. The horizontal dashed black line represents the ICRH antenna working frequency, ω_{ICRH}. The intersection points between ω_{ICRH} and the cyclotron frequency curves indicate the radial locations of the corresponding ion cyclotron resonances, which are crucial for IC wave absorption. Considering $\omega_{\text{ICRH}} = 60$ MHz, the resonance point with ^{3}He is clearly visible in the plot.

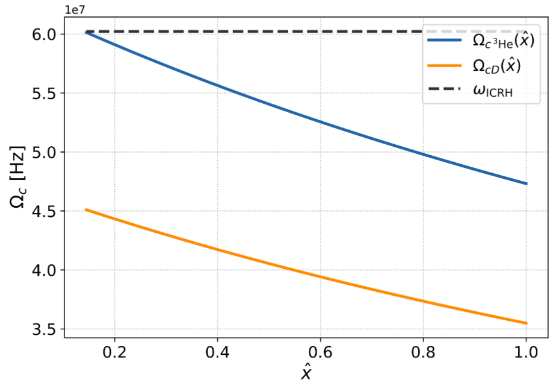


Figure 1. Radial profiles of ion cyclotron frequencies $\Omega_{cD}(\hat{x})$, $\Omega_{c^3\text{He}}(\hat{x})$, and the ICRH antenna frequency ω_{ICRH} (black dashed line), showing the expected resonance region.

In order to design and optimize a suitable 3-strap antenna model, the commercial RF simulation software CST Microwave Studio has been employed. Here the plasma has been replaced by an equivalent, isotropic, homogeneous, dielectric load ($\epsilon_r = 225$, $tang\delta = 1.17$ at 90 MHz) and a vacuum interlayer between the latter and the antenna [6]. The properties of dielectric load were derived emulating the antenna behaviour in front of a single-null DTT reference plasma. After an update of DTT scenarios, such dielectric properties were found to underestimate the actual value of coupled power. The frequency response is anyhow correctly reproduced, so the antenna optimisation work kept using them, being independent on the absolute value of coupled power. The three-strap antenna modeled in CST/MWS is shown in Figure 2, along with its starting fundamental dimensions. The CST/MWS early model is composed of: a) the antenna box, composed of three housings, one for each strap; b) the Faraday screen, composed of a fixed number of equally spaced rods; c) the three straps: the central one is fed by two coaxial cables, operated with a phase difference of 180 °, the side ones have mirror symmetry and are fed each by a single coaxial, connected to a strip line. The coaxial characteristic impedance is equal to 30 Ω. The goal of the CST/MWS modelling was to optimize the antenna structure in order to couple a power ≥ 1.5 MW to the dielectric load with a progressive phase shift of 180 ° between toroidally adjacent straps. In CST/MWS model, some parameters have been fixed by the geometrical constraints of DTT vessel and ports, while the remaining others, such as straps and housing dimensions, have been studied and modified for the tuning purpose.

A detailed parametric study has been performed on the antenna main dimensions with the objective to maximize the minimum conductance, or $G_{min,tot}$, that is related to the

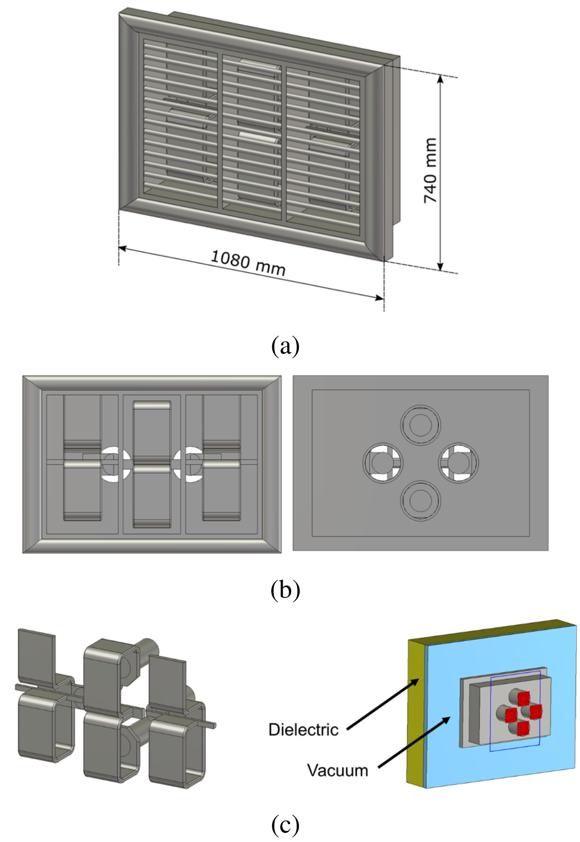


Figure 2. DTT ICRH 3-strap antenna flat model: (a) perspective; (b) front and back view of the structure; (c) detail view of the three straps and representation of the simulation domain in CST/MWS.

maximum power delivered to the dielectric load through

$$P_{coupled} = \frac{1}{2} G_{min,tot} V_{standoff}^2 \tag{1}$$

where $V_{standoff}$ is the maximum allowable voltage in the four coaxial cables, which is assumed equal to 35 kV in DTT [7]. After a tuning campaign, performed by varying the antenna dimensions, a coupled power of 1.38, 1.67 and 1.71 MW has been obtained at the operating frequencies of 60, 75 and 90 MHz respectively. Figure 3 shows the minimum conductance curve obtained at the end of the optimization procedure. Once the optimum configuration in terms of coupled power has been found, a visual and quantitative inspection of the electric field on the whole assembly has been carried out. In the case of electric field values, everywhere inside the antenna box, $|E|$ shall be ≤ 2.5 MV/m and $|E_{\|}|$ shall be ≤ 1.5 MV/m, as stated from DTT guidelines [7]. The electric field of the structure has been optimized by properly adjusting the antenna distance from the containing box walls and by smoothing the strap side edges; final results are shown in Figure 4.

It should be stressed that the equivalent dielectric approach only provides a first-order approximation of the coupled power, since the actual values depend on the plasma density profiles. Nevertheless, benchmark simulations performed with TOPICA, including a real-scenario

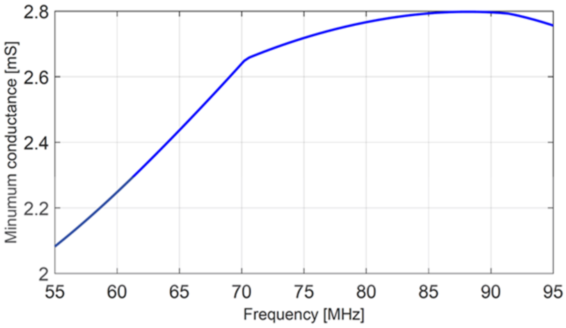
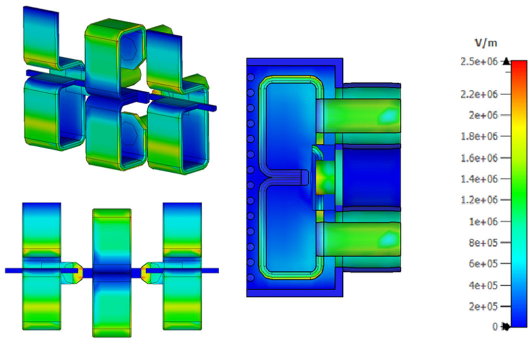
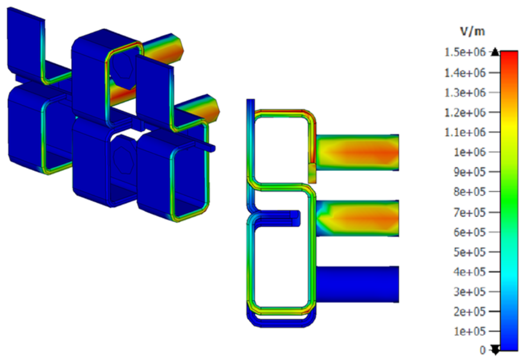


Figure 3. DTT ICRH 3-strap antenna flat model $G_{min,tot}$ curve obtained after the parametric optimization.



(a)



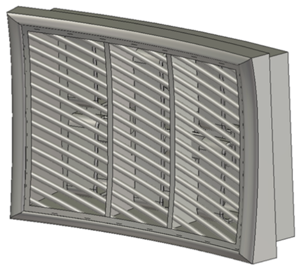
(b)

Figure 4. DTT ICRH 3-strap antenna flat model electric field surface plot: (a) $|E|$ on antenna straps; (b) $|E_{||}|$ on antenna straps. Simulation has been performed by imposing the coaxials to work at the maximum allowed voltage (35 kV) with a progressive phase shift of 180 ° between toroidally adjacent straps. Values are compliant with DTT specifications.

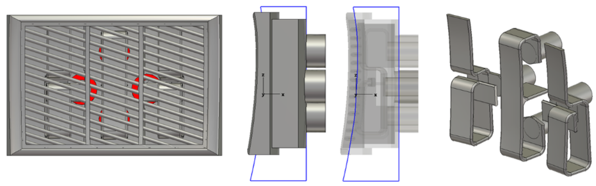
plasma load, yielded comparable coupled power values, thus confirming the validity of the adopted approach while allowing a faster parametric optimization.

3 ICRH 3-strap curved antenna design

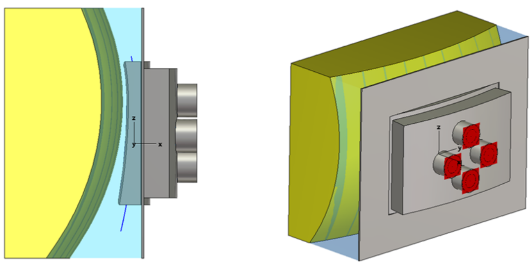
Starting from previous flat antenna model, the next step has been the design and the optimization of the curved 3-strap antenna launcher. The curved antenna, visible in Figure 5 employs poloidal and toroidal curvatures suitable to better couple RF to DTT plasmas while satisfying DTT mechanical constraints [8]. In CST the plasma has been replaced by the previously defined standard, isotropic, dielectric layer of proper relative permittivity (see Section 2). After a parametric optimization, $P_{coupled}$ values of 1.16, 1.27 and 1.04 MW have been obtained. The electric field, $|E|$, on strap surfaces is reported in Figure 6. Table 1 reports the comparison, in terms of coupled power, between the flat and curved antenna models previously discussed. The systematically lower coupled power obtained with the curved antenna, also confirmed by TOPICA simulations, can be explained by geometrical effects: the longer straps and their curvature modify the current distribution and near-field pattern, thus reducing the coupling efficiency with respect to the flat configuration.



(a)



(b)



(c)

Figure 5. DTT ICRH 3-strap antenna curved model: (a, b) different views of the full structure; (c) detail view of the simulation domain in CST/MWS.

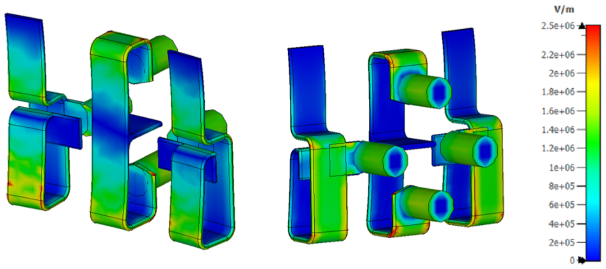


Figure 6. DTT ICRH 3-strap antenna flat model electric field module surface plot on strap surfaces. Simulation has been performed by imposing the coaxials to work at the maximum allowed voltage (35 kV) with a progressive phase shift of 180 ° between toroidally adjacent straps. Values are compliant with DTT specifications.

Table 1. $P_{coupled}$ calculated at the three operating frequencies for the flat (a) and the curved (b) antenna models.

	P_c (a) [MW]	P_c (b) [MW]
60 [MHz]	1.38	1.16
75 [MHz]	1.67	1.27
90 [MHz]	1.71	1.04

4 Conclusion and perspectives

The design and optimization of a 3-strap antenna for DTT ICRH system has been carried out using the commercial simulator CST Microwave Studio with the objective to couple a power ≥ 1.5 MW to a properly chosen dielectric load. The optimization started with the creation of a simplified antenna flat model and then proceeded with the design of the curved model that employs the correct poloidal and toroidal curvatures of the real machine. After the optimization, $P_{coupled}$ values of 1.16, 1.27 and 1.04 MW have been obtained at the operating frequencies of 60, 75 and 90 MHz. At the same time, the electric fields on antenna surfaces have been minimized to be compliant with DTT specifications ($|E| \leq 2.5$ MV/m and $|E_{\parallel}| \leq 1.5$ MV/m on antenna surfaces). Next steps will consist in a structure final optimization, to further increase the coupled power and decrease the detrimental electric field values on structure surfaces.

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