

Recent Progress in 3D Electromagnetic Modeling of the ITER ICRH

Antenna

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Introduction

A design of the antenna foreseen for ion cyclotron resonance heating (ICRH) of the ITER plasma has been developed previously [1] and consists in an array of 24 radiating straps grouped in poloidal triplets fed by means of 8 four-port junctions (4 top and 4 bottom). We start from the design of the antenna dating from October 2007 [2] (see figure 1) and we present in this work an electromagnetic study of its performances. We will show that this design is far from being optimal from an RF perspective and we propose a couple of substantial modifications which allow to almost double the amount of RF power that can be coupled to the plasma for a given maximum voltage. This optimization is based on CST Microwave Studio[®] [3] (MWS) simulations of one eighth of the array (i.e. one triplet of straps and its 4-port junction) with the plasma loading being approximated by a slab of ordinary dielectric. This latter approximation has been shown to give fairly agreeing results when compared to experimental loading [4].

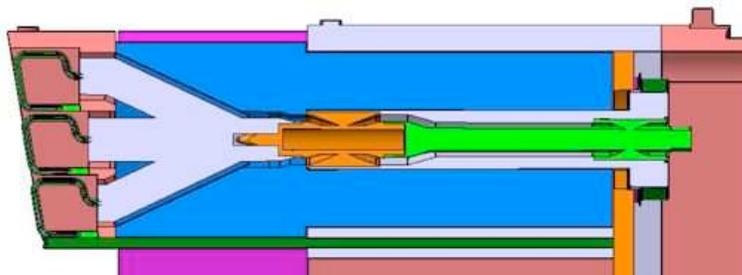


Figure 1: ITER antenna: Cut view of the October 2007 mechanical design [2]

Optimization strategy

The triplet and its junction can be described in the framework of the transmission line theory. A circuit diagram of the feeding line of one triplet of straps is displayed in figure 2. In all regions the active power which can be coupled to the plasma is given by

$$P = G_{min} \frac{|V_{MAX}|^2}{2} \quad (1)$$

where G_{min} is the minimum conductance in the considered region. If we assume a given maximum voltage in the line $|V_{MAX}|$, we see that maximizing G_{min} will also maximize the power

P for a given characteristic impedance Z_0 . Practically we can try to optimize the design by modifying the parameters of the antenna box. Indeed the strap input impedance is given by $Z_F = R_F + iX_F$ with $R_F^2 \ll X_F^2$ and the geometry of the box acts on the strap input resistance and reactance hence on the conductance:

$$G_{min1} = \frac{G_F}{1 + \frac{Z_{01}^2}{X_F^2}} \text{ with } G_F = \frac{R_F}{X_F^2}. \quad (2)$$

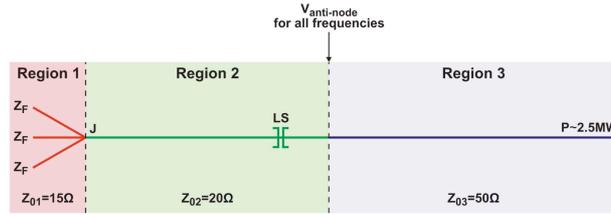


Figure 2: Circuit diagram of the feeding of one triplet of straps. Region 1: strap triplet and four-port junction. Region 2: 20 Ω feeding line section. Region 3: 50 Ω feeding lines.

The current in the antenna box being given either by

$$|I_{antenna}| = \frac{|V_{MAX}|}{\sqrt{X_F^2 + Z_{01}^2}} \text{ or by } |I_{antenna}| = \sqrt{\frac{2P}{R_F}}, \quad (3)$$

it will also increase in the process and should be kept to an acceptable level.

The maximum G_{min2} achievable is exactly $3G_{min1}$ in the optimal case of an ideal junction located at a voltage anti-node. Trying to be as close as possible of an ideal junction will be the main motivation of the second stage of optimization.

Modeling results

Three geometrical characteristics of the antenna box have been modified to increase the power coupling to the load: the shape of the connection between the strip line and the feeding coaxial, the width of the strap and the depth of the antenna box. As a first step we have replaced the "S"-shaped transition by a more continuous one called a "loft". The more continuous impedance transition between the coaxial line and the strip line has a positive effect on the coupling properties. We obtain an improvement in coupling comprised between 17 % (at lower band edge) and 27 % (at mid-band). In a second step we have modified the antenna box in two ways: increasing the width of the strap and reducing the depth of the strap box. By varying the strap width between 170 mm and 280 mm, we see in figure 3 that it is possible to significantly increase the minimum conductance in region 2 (G_{min2}) but this occurs at the expense of a shifted optimal frequency. This effect can be partially compensated by increasing the length of the coaxial arms

of the four-port junction: this re-locates the junction point at a voltage anti-node. Unfortunately we also observe that this decreases the maximum G_{min2} achievable. Similar conclusions can be drawn when the box depth is varied. Therefore a compromise between the optimal G_{min2} and the frequency centering must be found. The optimization of the antenna box led to the following set of parameters: $strap_w = 210$ mm, $box_d = 285$ mm, and $l_{add} = 85$ mm. The enhancement of coupling is comprised between 20 % and 36 % (mid-band).

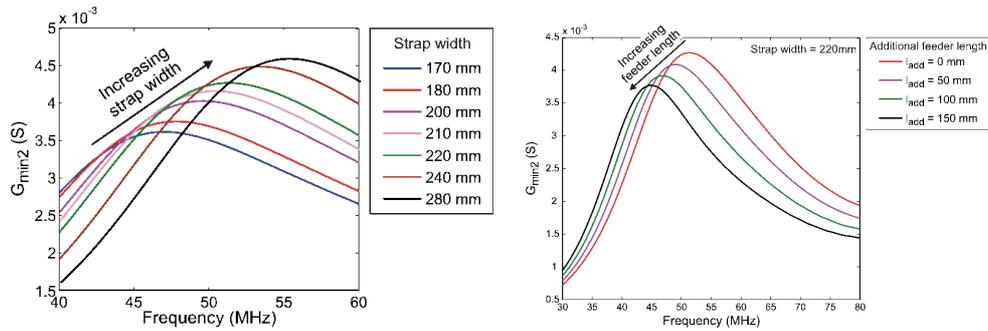


Figure 3: Left: G_{min2} vs frequency for the ITER antenna model with a lofted transition for varying strap width. Right: G_{min2} vs frequency for the ITER antenna model with a lofted transition and strap width of 220 mm. Various values of the additional length of coaxial line in the arms of the four-port junction are considered. All the other parameters are constant.

We come now to the four-port junction. Historically the shape of the junction was designed to maintain a constant characteristic impedance (20Ω) between the 20Ω feeding coaxial line and the three lines connected to the each strap [1]. This was judged to complicated to realize and was revised leading to the reference October 2007 mechanical design shown in figure 1. The junction has a triangular shape and is centrally fed. Obviously the requirement to maintain a constant characteristic impedance is no longer respected and the region of undefined impedance significantly alters the ideal character of the junction in terms of transmission lines with further effects on the performance of this design. A method for avoiding this effect is to shorten the region of the junction where the impedance is undefined by reducing the value of the angle between the 20Ω input coaxial and the triangular zone around the junction point. We have varied this angle starting from the reference value of 155 degrees to a minimum value of 90 degrees (see figure 4). The effect on the terms $|S_{11}|$ and $|S_{23}|$ is shown in figure 5: the junction is becoming closer to the ideal one as the angle is reaching 90 degrees, i.e. as the non-coaxial zone is being reduced. It is obvious that we should create a junction with coaxial lines and curved profiles. Therefore we have proposed a new design of the four-port junction (see figure 4) characterized by a coaxial cross-section and a circular profile. Figure 5 shows that a significant improvement is obtained with this new junction. The improvement in G_{min2} can reach 91 % at

mid-band and, unlike the antenna box optimization, has no impact on the antenna current.

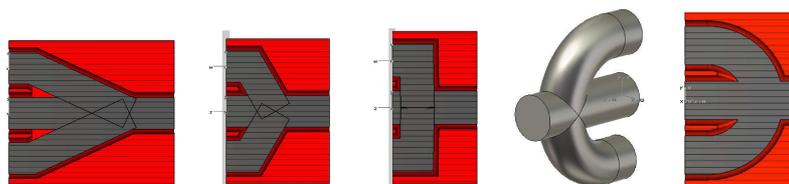


Figure 4: Four-point junction models for various junction angles. From left to right: 155°(reference); 120°; 90°; optimized model: profile of the inner conductor and cut view of the junction inside its box.

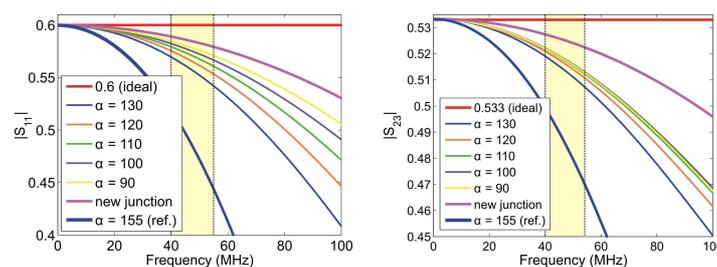


Figure 5: $|S_{11}|$ and $|S_{23}|$ as a function of the frequency: 4-port junction with various angles are compared with ideal junction and with optimized junction.

If we now combine the various improvements suggested previously, we have computed that it is possible to almost double the coupled power at mid-band with this new design. Significant improvement at the band edges (60 % at 40 MHz and up to 165 % at 55 MHz) can be obtained by the inclusion of a 15Ω service stub (provided it is positioned at $\lambda(47.5\text{MHz})/4 = 1.58$ m from the electrical junction point).

Conclusion

A Microwave Studio[®] model of the ITER ICRF antenna (October 2007 design) has been developed and used to perform a parametric study of the array and an RF optimization. This has allowed to develop a new reference design leading to, for a given maximum voltage, a gain of almost 100 % of coupled power at mid-band. This design is being validated on a reduced-scale RF mock-up and by other codes.

References

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