Conceptual design of an ICRH antenna for W7-X: modeling and optimization

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Introduction

Ion Cyclotron Resonance Heating (ICRH) is a promising heating and wall conditioning method considered for the W7-X stellarator. For a magnetic field of approximately 2.5 T various minority heating scenarios are being considered: minority He^3 in H or in He^4, and He^3 in D at 25 MHz, minority H in He^4 or in D at 38 MHz and 76 MHz. Therefore two frequency ranges (25-38 MHz and 76MHz respectively) are necessary to cover all the heating scenarios and a satisfactory conceptual antenna design should in theory be able to couple power in a very broad frequency range. Various conceptual designs have been proposed for this aim and we will present in the next sections electromagnetic studies of their performance. The tridimensional electromagnetic software CST Microwave Studio [1] (MWS) has been intensively used for this purpose: MWS allows for a very detailed modeling of the geometry of the antenna and gives as results scattering matrix for a set of defined ports (usually at the back of the straps feeders) and input impedance/admittance matrices, as well as detailed distributions of the electromagnetic fields on the conductors. Nevertheless MWS does not contain any model of a magnetized plasma and a set of stratified isotropic dielectric layers equivalent to the given density profile is used to simulate plasma loading [2], the equivalent permittivity being given by $K_D(x) \approx (c/V_A)^2$ where c and V_A are, respectively, the light velocity and the Alfvèn velocity. For the present work a K_D profile equivalent to the reference W7-X plasma density profile (see [3]) has been used.

Study of an antenna conceptual design

We propose to study various antenna plug-in concepts with a simple flat model of the front face coupled to lumped tunable capacitors. The antenna box is 740mm high and 340mm wide. We consider two short-circuited long straps in phase opposition with a coaxial line at the top (resp. ports 1 & 3) and one approximately central tap feed (resp. ports 2 & 4). MWS is then used to compute the 4X4 scattering matrix of the 4-port network describing the dielectric facing antenna. This matrix is inserted into a circuit model including lumped tuning capacitors

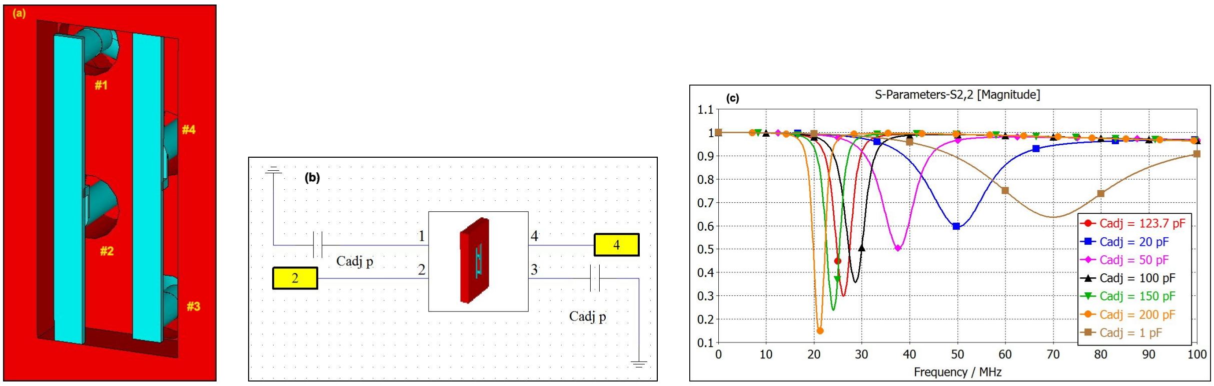

Figure 1: Conceptual design of the ICRF W7-X antenna: (a) MWS model of the front face; (b) circuit model; (c) scattering term $|S_{22}|$ for various values of the adjustable capacitance C_{adj}

connected to ports 1 & 3. Figures 1 (a)-(b) show the conceptual design and its circuit model. In this concept the adjustment of the capacitor will tune the resonator made of the strap reactance and the capacitor to a certain frequency where the scattering term is minimum and the coupling maximum: see figure 1 (c). If the resonance frequency can be adjusted within a broad frequency range, it is not possible to cover the whole range [25-76] MHz required by the various heating scenarios. The presented concept is therefore appropriate for the low-frequency range (25-38 MHz), and a different concept is needed for the high-frequency range (76 MHz). For this latter case we propose another plug-in with each long strap split in triplets fed in parallel by a 5-port junction: see [3] for a preliminary layout of the plug-in and its matching system.

Simulation and optimization of the low-frequency antenna

MWS has been intensively used to predict and optimize the performance of a simplified geometry of the low frequency design. The antenna must couple as much power as possible and we know from [4] that the RF power coupled to the plasma can be substantially increased by modifying some geometrical parameters of the strap box geometry (strap width, box depth, connectors). However unlike in the ITER case the performances of the antenna are limited by the various constraints on the capacitors: maximum currents ($|I_{C,max}| = 800$ A) and maximum voltage ($|V_{C,max}|$ = 42 kV) on the capacitor, and tuning capacitors range (15pF $< C_{adj,DC} <$ 200pF). For a given geometry MWS computed the 4X4 scattering matrix which is afterwards inserted into a circuit model where we connected ports 1 & 3 to the tuning capacitors and imposed $|I_1| = |I_3|$. From a scan in capacitance (the same value for both capacitors) we can deduce the tuning capacitance C_{adj} for which the averaged minimum conductance G_{min} in the feeding lines connected to port 2 & 4 is maximum, with $G_{min} = 2P/|V_{max}|^2$, at a given frequency (V_{max} is the antinode voltage) and for a given toroidal current phasing. This value C_{adj} allows

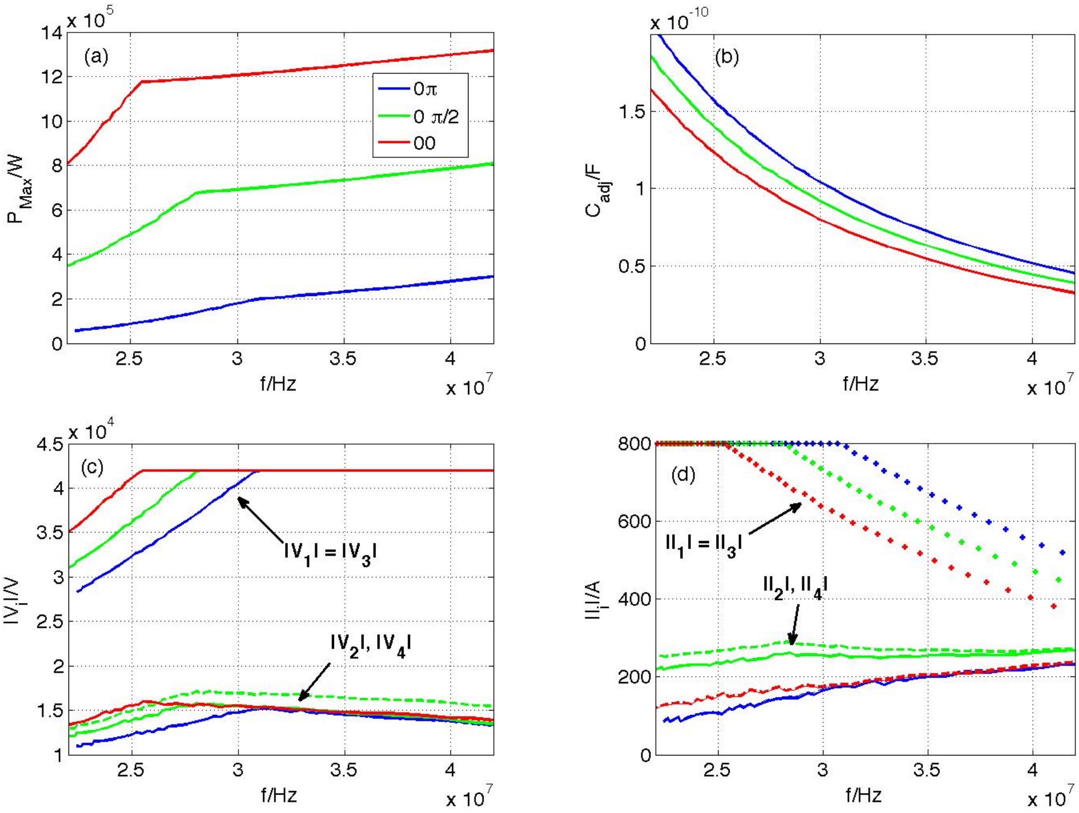

Figure 2: Performance prediction of the tunable 2-strap antenna (low-frequency range) for different toroidal current phasings (see color code in figure (a)): (a) Total maximum coupled power (b) Tuning capacitance vs frequency (c) Voltage amplitudes at capacitors ports 1 & 3 and tap ports 2 & 4 (d) Current amplitudes at capacitors ports 1 & 3 and tap ports 2 & 4.

to compute the 2X2 scattering matrix of the resulting 2-port network, and the various voltages, currents at each port, as well as the maximum power which can be coupled to the plasma accounting for the various limitations mentioned earlier (see also [3]). Results for the initial geometry (see Figure 1(a)) are shown in figure 2. An inflection point is clearly visible in figure 2(a) where the transition between the regime dominated by $|I_{1,3}| = |I_{C,max}|$ to the regime where $|V_{1,3}| = |V_{C,max}|$ occurs. This corresponds to $|I_{C,max}| = |V_{C,max}|\omega C_{adj}$.

This initial geometry has been optimized in successive steps. In a first step (labeled "Optimized geometry 1") we have exploited the fact that some space was still available around the plug to increase the size of the antenna box by 14cm (from 74 to 88cm) and the length of the strap by approximately the same amount. In a second step we have redrawn the geometry of the tap feed: instead of a "L"-shaped structure we considered a smoother inclined plane from the central coaxial to the strap, avoiding discontinuity and right angles (see figure 3(a)). This geometry is labelled "Optimized geometry 2". Figure 3(b) shows how each transformation influences the maximum power coupled to the load in function of the frequency: the position of the inflec-

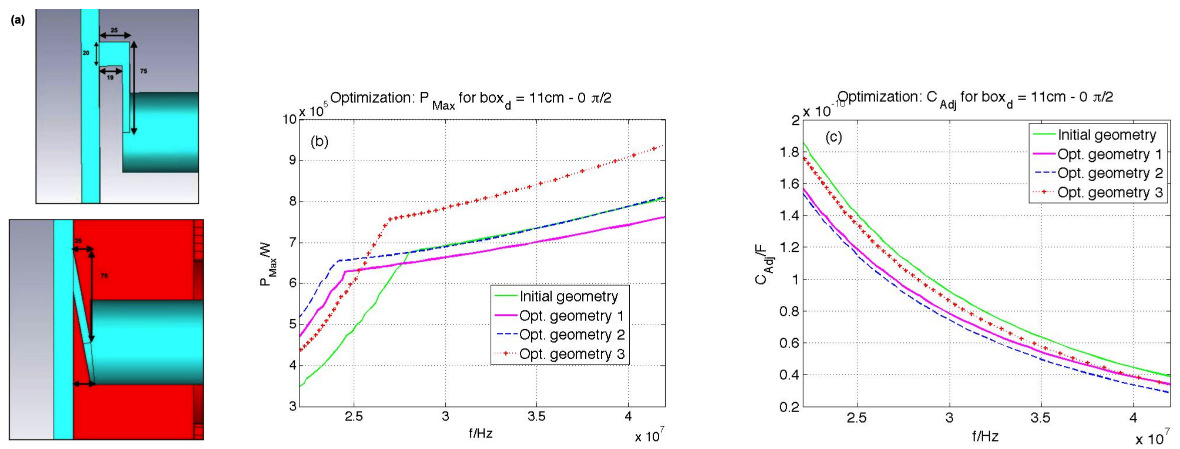

Figure 3: (a) detail of the geometry of the tap feed (top: initial, bottom: optimized); (b) Maximum power coupling and (c) Tuning capacitance vs frequency for each step of the geometry optimization (see text for definition) in 0 $\pi/2$ toroidal phasing.

tion point is critical and determined by each geometry, making difficult to get an homogeneous increase in power in the whole frequency range. This is basically around 25 MHz that the optimization from the initial geometry to the geometry "2" gives the most significant effect. The performance at 38 MHz is barely changed. Importantly these transformations decrease C_{adj} (see figure 3(c)) which can get very close to the lower boundary of the vacuum capacitor. Finally we have performed a scan in strap width (initially is 68mm) and box depth (initially 11cm). If this latter parameter barely influences the results, the increase in scan width steadily offsets the inflection point towards larger frequencies. Consequently the performance degrades at 25 MHz, but improves at 38 MHz. Furthermore the adjustment capacitance increases due to lower strap input reactance. It is therefore a good compromise to slightly increase the strap width to 9cm: this avoids a too low capacitance at 38 MHz, uniformly increases the power coupling in almost the whole band and minimizes the coupling decrease at low frequency.

References

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