A Novel Approach to Ion Cyclotron Antennas for Nuclear Fusion Experiments

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***Abstract*—In nuclear fusion experiments, one of the most assessed methods for heating plasma is via transfer of electromagnetic energy in the Ion Cyclotron Resonance Frequency (ICRF) range. However, space constraints for the plasma-facing antennas result in poor impedance matching and high electric fields; for these reasons current antennas cannot efficiently couple high power to the plasma and require complex matching circuits. This preliminary study presents a new perspective on designing tunable resonant antennas, based on quarter-wavelength resonances.**

***Index Terms*—Plasma, TOKAMAK, Tunable Antenna, Ion Cyclotron.**

I. Introduction

Ion Cyclotron Resonance Frequency (ICRF) antennas designed for nuclear fusion experiments like ITER [1], DEMO [2], DTT [3], SPARK [4], and EAST [5] face challenges due to space, electro-mechanical constraints and the large amount of power transferred to the plasma. Due to space limitation and the operation wavelength, these antennas are characterized by a high reflection coefficient at the feeding coaxial lines (standard impedance of 30 Ohm). Complex, resonant matching circuits handle impedance mismatch, leading to high voltage issues in the antenna feeding and matching lines. Also, this is associated with high electric fields around the antenna, leading to sputtering from the front face. It is therefore crucial to design antennas that can handle and possibly solve these problems. One potential approach is to use self-resonant antennas.

This is the aim of this communication. This study started a few years ago, proposing self-resonant antennas based on quarter-wavelength resonances [7]. Here we study a configuration dual to the one in [7], with possible lower fields but additional challenges.

II. Resonant Antennas

As well known, a (one port) structure is defined to be resonant if its input impedance $Z_{in}(f)$ is purely real at the reference frequency f_0, i.e. $\mathrm{Im}\{Z_{in}(f_0)\} = 0$, $Z_{in}(f_0) = R$. This is not yet enough to make the structure practically usable; the real part of the input impedance at the resonance frequency should match the desired value set by generators and feeding line, R_0; the latter in typical IC systems is of the order of a few tens of Ohms.

In typical ICRH systems, this necessary resonance property is achieved after the tuning and matching system (TMS), located outside the vacuum chamber, as the antenna alone cannot reach this condition. On the contrary, a self-resonant antenna is characterized by this property at its port; this may relax the task of the TMS or even remove its need altogether.

It is also well known that the (self) resonance of antennas happens when the electrical length is comparable to the wavelength; in a first approximation, we can employ here the vacuum wavelength $\lambda \approx \lambda_0 = c/f$ (the impact of plasma is minor on these considerations). Conventional IC types of antennas, such as the strap topology (in essence a loop-type launcher), require that the length L of the antenna is $L \approx \lambda/2$, which implies sizes typically unavailable in most machines. A less known fact is that the very first resonance happens for the loop antenna at $L \approx \lambda/4$. This resonance is characterized by a very high real impedance, which makes it useless for our purposes unless an impedance reduction is somehow achieved.

III. Simulation setup and tested solution

In our past works, we have analyzed several antenna geometries [6] and carried out the optimization of the most promising one [7]. Since the aim was to design a launcher that could be operated in matched conditions on a frequency band, usually going from 30 MHz to 90 MHz, a few tuning elements (TE) were inserted in the design to provide that flexibility. The entire preliminary analysis was carried out with the help of the commercial software CST Studio Suite. The plasma load was approximated by a 60.8 mm vacuum layer located right in front of the Faraday Screen (FS) outer surface, and by a user-defined lossy dielectric ($\epsilon_r = 225$ and $tan\delta = 1.17$ at 90 MHz) extended for an additional 400 mm. We stress that a comprehensive design, including thermal and nuclear considerations, was and still is beyond the scope of our study. It is also worth noting that we adopted a conventional 50% transparency factor of the FS and that we used rounded bars with a cross-section of approximately 25 mm to facilitate cooling. We refer the interested reader to [6] and [7] for the complete discussion on the preliminary analysis and the subsequent optimization.

In this paper, we further explore one of the discarded designs, (labeled geometry S2 in [6]), shown here in Figure

1A. The radiating element consists of a passive (secondary) loop, driven through an active (primary) loop in the back. In other words, the antenna feeding behaves as a transformer to match the expected high impedance of the resonant (passive) loop. The main advantage of this geometry is the reduction of the electric field within the antenna cavity, which appeared to be the main weakness of the previously analyzed solutions. No tuning has been considered in this preliminary study.

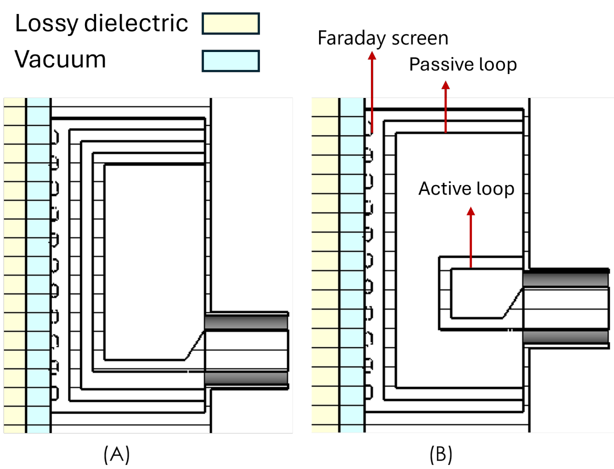

Fig. 1: Initial geometry (A) versus first optimization (B)

Figure 2 shows the complex input impedance at the antenna port for geometry A; the reader can notice a first resonance around 70 MHz, characterized by a real part of approximately 11,000 Ω.

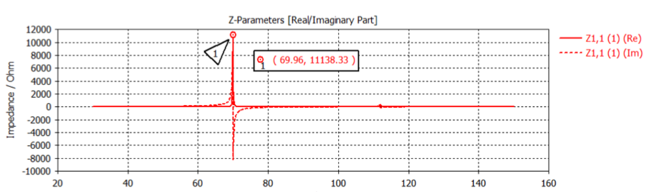

Fig. 2: Input impedance (continuous line for the real part, dashed line for the imaginary part) for geometry A.

The real input impedance has been reduced to 182 Ω by increasing the distance between the active and the passive loop, by reducing the total size of the active loop and eventually by slightly moving the position of the port towards the center, as documented in Figure 1B. Figures 3 and 4 report both the antenna input impedance and the input reflection coefficient for this new geometry.

Despite the huge reduction in terms of input impedance value, the resonance has been up-shifted in frequency to 110 MHz, i.e. out of the operative frequency range of IC antennas. Besides, the position of the active loop quite effectively reduces the available space for the implementation of a TE, which is necessary to tune the resonance to the desired frequency.

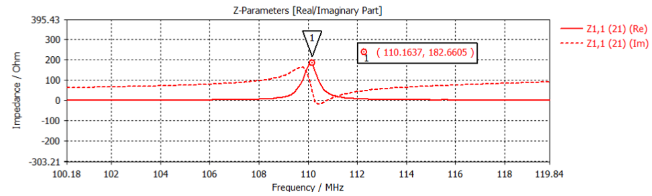

Fig. 3: Input impedance (continuous line for the real part, dashed line for the imaginary part) for geometry B.

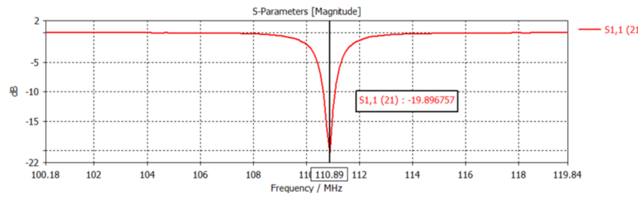

Fig. 4: Input scattering parameter (in magnitude) for geometry B.

IV. Conclusions

This paper presents a full-metal self-resonant antenna concept that, while not an optimal solution, is an interesting alternative for future optimization and application in fusion experiments. The investigated launcher shows a very promising input reflection coefficient. However, further optimization is required to reduce the working frequency and to insert a tuning element able to shift the resonance within the typical IC frequency band.

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