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An ICRF Strap Antenna Solution Exploiting the High Impedance Technique

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Abstract. Ion Cyclotron Range of Frequencies (ICRF) strap antennas are routinely adopted in most of the existing nuclear fusion experiments, even though their main goal, i.e. to couple high power to the plasma (MW), is often limited by rather severe drawbacks due to high fields on the antenna itself and on unmatched part of the feeding lines directly connected to the antenna. In this work, we propose, describe, prototype and measure an ICRF strap antenna based on the high impedance surfaces concept that is matched at a specific tunable frequency. The adopted high-impedance structure, positioned between the strap and the backwall, is a metallic patch displaced on top of a dielectric block and grounded by means of a vertical post, in a mushroom-like shape. This structure presents a high impedance, within a given very narrow frequency band, such that the image currents are in-phase with the currents of the strap itself, thus determining a significant efficiency increase. After a general description on the properties of high impedance surfaces applied to ICRF antennas, we describe the optimization steps, carried on by means of numerical codes, to define an antenna configuration suitable for a nuclear fusion experiment. The antenna has been then manufactured and measured; strengths and weaknesses of the proposed solution are outlined.

MOTIVATION AND BACKGROUND

Ion Cyclotron (IC) antennas are certainly one of the most promising options to deliver high power to the plasma in present-day magnetically confined nuclear fusion experiments. As a matter of fact, IC antennas are currently installed and routinely operated in almost all the existing experiments and they are foreseen for the next generation of tokamaks.

Unfortunately IC launchers, if compared to antennas used in radars or telecommunications, are characterized by very poor loadings, i.e. by very high reflection coefficients at their input ports. To be more specific, the working frequency (usually of the order of tens of MHz), the high power to be delivered to plasma, the limited space available on the machines and, in general, the mechanical constrains do not allow to easily reach an efficient antenna design. This practically means that, in order for IC systems to be successfully operated in plasma fusion experiments, extremely high voltage values have to be imposed along the input lines, between the antenna and the mandatory matching system. As one may guess, high voltages are rather dangerous for the feeding lines, leading to breakdowns especially at the feedthroughs, and for the antenna itself, above all around the radiating elements, causing arcs and driving RF potentials that can eventually damage the entire system. Given these conditions, even a small reduction of the input reflection coefficient would determine a consistent gain in terms of power transferred to plasma (at constant voltage) or, even better, a huge decrease of the input voltage (at constant delivered power).

In this respect, [1] introduced for the first time the concept of high impedance surfaces (HIS) to IC antennas. Even though originally conceived for wireless devices such as cellular phones, [1] reported that HIS could be exploited also on IC antennas, producing a reduction of the reflection coefficient at the input ports and, hence, a considerable increase of the antenna efficiency. Similarly, [2] proposed a HIS application also to current drive high harmonic antennas in view of the DEMO reactor.

This paper describes an IC antenna implementation of HIS that can be fitted into existing experiments. It is important to remark that only a proof of concept is provided, without addressing mechanical, thermal and nuclear stresses. The organization of this paper is as follows: in Section a) an overview of the HIS technique is provided, Section a) shows how the resonant frequency can be tuned through proper design and contains the implementation of

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this concept into a scaled IC antenna mock-up.

HIGH IMPEDANCE SURFACES AND APPLICATION TO IC ANTENNAS

While referring the interested reader to [3] for a detailed mathematical analysis of the HIS design and to [1] for the application to IC antennas, we would like to provide here a short overview of the topic.

HIS are periodic metallic structures (patches) displaced on top of a dielectric or vacuum substrate and grounded by means of vertical posts embedded inside the dielectric. If the length of the posts is small compared to the wavelength, HIS can be described by an equivalent lumped circuit model made of capacitors and inductors: the gap between the patches provides the capacitance, while the conducting path linking them together is responsible of the inductance. Figure 1 reports a simplified side view of these mushroom-like surfaces.

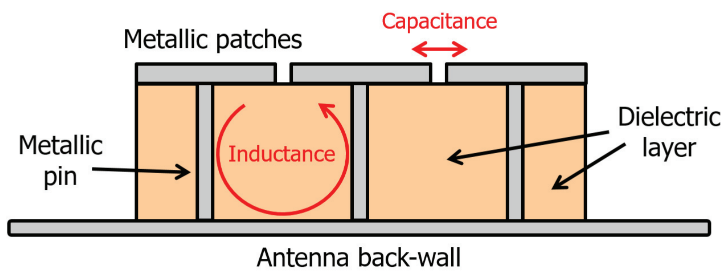

FIGURE 1. Cross section of a single layer high impedance surface structure.

HIS can be therefore seen as electric filters operating in a specific and tunable frequency band; geometrical modifications of the patches or variation of the dielectric layer properties can affect the equivalent capacitance and inductance and, as a consequence, the resonance frequency. More generally, in terms of working properties, HIS are electrically thin in-phase reflectors with surface wave suppression. On the one side, despite being electrically thin, their surface presents a high impedance within a given frequency band such that the image currents are in-phase with the currents of the antenna itself. This property is crucial for IC antennas, where, due to the limited space in the back, image currents are naturally not in phase with strap currents, resulting in a consistent loss of radiation efficiency. On the other side, since surface waves are suppressed on the same frequency band, no power is lost into the dielectric layer. Considered together, these two properties determines a significant efficiency increase.

As already claimed, these structures resonate at a fixed frequency, being this their main limitation. However, as indicated in [2], sliding poles can be manufactured to slightly adjust the resonance frequency; this feature is mandatory to take care of varying loading conditions in a fusion experiment. Furthermore, it should be stressed that, if working out of the chosen frequency band, high impedance surfaces do not have deleterious effects on the launcher, which performs as in their absence.

PARAMETRIC DESIGN ANALYSIS AND SCALED MOCK-UP RESULTS

A single strap HIS antenna has been optimized to operate around 30MHz with the help of CST-MWS. Figure 2 shows the main dimensions and the structure of the IC launcher; as mentioned above the size of the proposed antenna is compatible with existing machines.

One HIS structure has been inserted on the back of the strap, separated by a vertical septum from the strap feeder; the HIS has been equipped with a small layer of Duratec 750 material ($\epsilon_r = 7.7$) connected to the HIS top (in case of implementation of the concept to a nuclear fusion experiments alumina, $\epsilon_r = 9.9$, could be a suitable choice). The metallic pole is designed to allow active cooling (diameter equal to 5cm) and to radially shift in order to tune the resonant frequency. Figure 3 reports the dependence of the HIS resonance on the pole radial extension, both in terms of frequency and of magnitude; a 1cm gap between the HIS top and the back surface of the strap is set in case of the lower working frequency.

In general, a longer pole, a deeper box, and a higher electric permittivity of the dielectric layer are effective ways to shift the resonance to lower frequencies and to increase its magnitude. However, only the first option, i.e. the pole

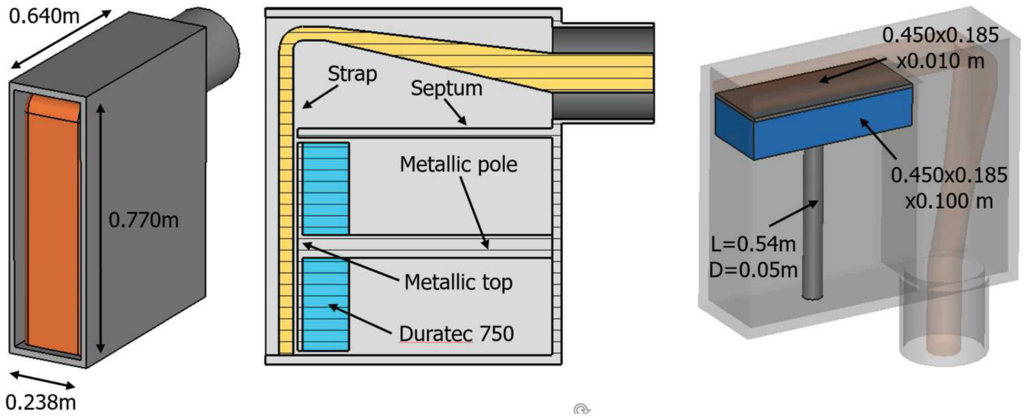

FIGURE 2. Antenna box dimensions (left), antenna structure (center) and HIS dimensions (right)

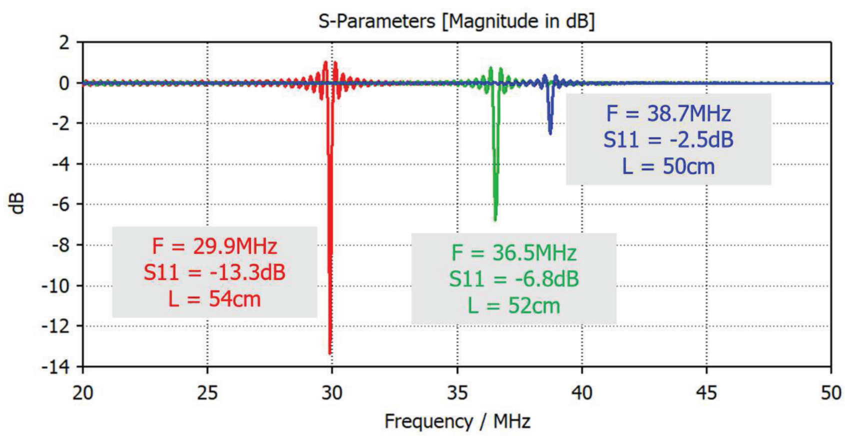

FIGURE 3. S_{11} magnitude as a function of the radial position of the HIS. "L" is the pole radial extension.

radial shift, can be exploited during a fusion experiment without entering the port plug; also in that case, the lower frequency is determined by the position of the strap (thus again fixed a priori), while higher frequencies can be reached by slightly retracting the HIS backwards in real time or between the shots. The antenna loading only slightly modifies the resonance position, allowing to optimize and test the antenna in vacuum; the pole shift is nevertheless crucial to perform small adjustments in operative conditions. The simulated electric current shows a typical quarter wavelength behavior at the resonance, while it is almost constant elsewhere in frequency. The current is also quite intense on the HIS pole at the resonance; for this reason the size of the pole has been chosen to allow active cooling. The electric fields are of no concern in front of the antenna, while additional optimization is required to exclude the presence of arching within the antenna box, between the HIS structure and the surrounding elements.

A scaled mock-up (scale factor 1:5) has been then manufactured in our laboratory in order to verify the CST-MWS predictions in terms of input parameters, as shown in Figure 4. The mock-up has been measured with a Network Analyzer in air (no loading) and similarly simulated with CST-MWS. The Duratec dielectric connected to the HIS top has been also removed to verify the behavior of purely metallic HIS. Figure 5 documents the comparison. The insertion of the dielectric layer determines a shift of the resonance towards lower frequencies; both simulations and measurements report this behavior and are in good agreement, even though a small discrepancy (few MHz) is observed, likely due to the manufacturing process (no manufacturing precision tools were used).

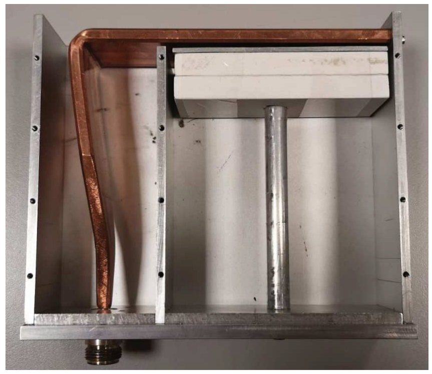

FIGURE 4. Side view of the scaled mock-up.

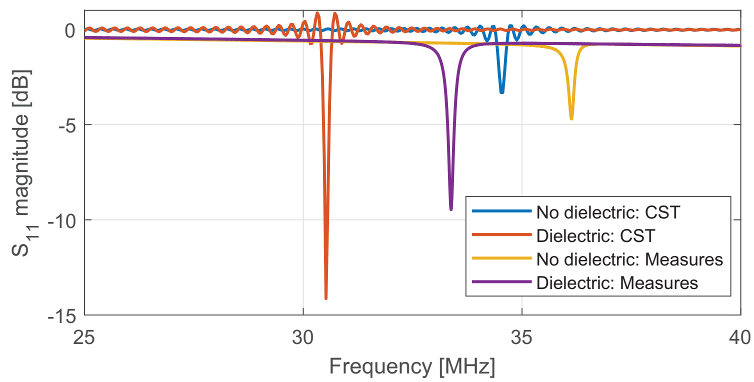

FIGURE 5. Comparison between simulated predictions and measured data, with and without the Duratec layer.

CONCLUSION AND PERSPECTIVES

The design outlined in this paper proved that the input mismatch of an IC antenna is considerably decreased in a narrow range of frequencies with the implementation of the high impedance surfaces. This solution permits to couple more power with a reduced input voltage and, hence, to operate an IC launcher with a significant efficiency increase. The overall dimensions of the proposed design are suitable for existing fusion experiments such as EAST, where a two strap antenna can be fitted. A preliminary thermal and mechanical analysis (not reported here) did not pointed out any specific concern with the design. Optimization is ongoing to reduce the electric fields magnitude within the antenna box during high power operations.

ACKNOWLEDGMENTS

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REFERENCES

1. D. Milanesio and R. Maggiora, Physics of Plasmas **21**, p. 061507 (2014).
2. D. Milanesio and R. Maggiora, “A demo relevant fast wave current drive high harmonic antenna exploiting the high impedance technique,” (2015) p. 4.
3. D. F. Sievenpiper, “High-impedance electromagnetic surfaces,” Ph.D. thesis, UCLA 1999.