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Nonlinear Effects of Electromagnetic Pulse on a Plasma-Based Electrically Small VHF Antenna

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Abstract—Demonstration of the electromagnetic hardening properties of a plasma-based electrically small VHF antenna is presented in this paper. It is shown that when illuminated by an electromagnetic pulse, the maximum voltage collected by the antenna grows linearly with the maximum magnitude of the incident electric field, but beyond a certain threshold around 70 kV/m, the maximum voltage collected ceases to grow linearly and seems to saturate around a value of 200 V.

Index Terms—plasma-based antenna, electromagnetic hardening, electrically small antenna, electromagnetic pulse

I. INTRODUCTION

Electromagnetic hardening consists in reducing the electromagnetic stresses that an equipment can undergo when it is subjected to an electromagnetic aggression [1]. More specifically, it consists of demonstrating that these constraints are lower than the equipment's susceptibility threshold. The latter is the threshold beyond which we observe non-tolerated events on the equipment, which can range from non-remanent malfunction to destruction. In an electronic warfare context, the transmission chains are priority targets, the main accesses of which being the antennas. In addition to transmitting or receiving the wanted signal, the antennas also collect electromagnetic waves associated with their operating frequency. These unwanted signals are then transformed as a current in the transmit chain which can disturb their operation. Thus, the antenna appears as a central element in the electromagnetic protection of the transmission chains.

Plasma discharges [2] have already shown promising results for the development of radio frequency or microwave systems with electromagnetic hardening properties [3]–[5]. Indeed, plasma discharges are media for which non-linear electromagnetic properties are observed when a high power electromagnetic excitation is applied to them.

In the case of antenna development, plasma discharges are generally exploited to provide antennas with frequency reconfigurability, beam-forming capabilities, and/or stealth properties [6]–[11]. These antennas mainly exploit two electromagnetic properties of plasma discharges due to its dispersive nature, its electric conductivity when the real part of its relative permittivity is largely negative [7]–[9], and its dielectric behavior when the latter is between 0 and 1 [10], [11].

Recently, a new type of electrically small plasma-based antenna has been proposed and experimentally studied in VHF band [12]. This antenna relies on the theoretical concept

proposed in [13]. In this case, the plasma behaves neither as a good electric conductor nor as a dielectric, but more particularly as a poor electric conductor, i.e. an Epsilon Negative (ENG) material. More specifically, the operation of the antenna is based on the coupling between a transmitting chain and the plasmonic resonance of electrons within a hemispherical plasma discharge [14], [15].

In addition to being electrically small and frequency reconfigurable, the association of the use of a plasma discharge for a resonant phenomenon suggests that this antenna presents potential electromagnetic hardening properties. In this paper, we present first experimental results pointing out electromagnetic hardening properties of such a plasma-based antenna.

II. PLASMA-BASED ANTENNA

Our plasma-based antenna corresponds to the one presented in [12]. However, this one having undergone some minor changes and for pedagogical reasons, this part aims at presenting the prototype in detail. Moreover, additional results on the performance of the antenna are given.

Fig. 1 shows a schematic of the plasma-based antenna while Fig. 2 shows two pictures of the antenna with and without plasma. It consists of a hemispherical glass shell positioned on a ground plane. The shell allows confining the plasma discharge. Its external radius is 107.5 mm, its thickness 5.5 mm, and its dielectric constant 5.5. The gas pressure inside the chamber is controlled by two sealed vacuum ports. The plasma discharge is created and maintained with an inductive RF source at 13.56 MHz. This source is a spiral coil with a Faraday shield [16] and a glass disk ensuring the vacuum seal. A small monopole of 5 cm long is inserted into the plasma through the center of the ground plane and allows the coupling between the transmission chain and the plasma discharge. In order to minimize the electromagnetic losses, the choice of the gas is important. Currently, the gas selected is a mixture of Neon with 1% Xenon at a pressure approximately equal to 10 mTorr (about 1.33 Pa). The electron density of the plasma, and thus its relative permittivity at a given frequency, is controlled by modifying the power injected into the inductive RF source.

Regarding the performance of the antenna presented in [12], a reflection coefficient lower than -10 dB was obtained between 290 MHz and 330 MHz. The radiation performance of the antenna was evaluated through the transmission coefficient between the plasma antenna and a coaxial probe positioned

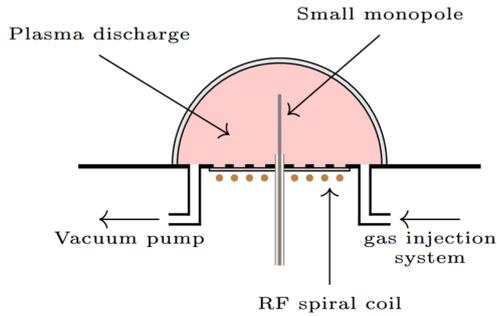


Fig. 1. Schematic of the plasma-based antenna.

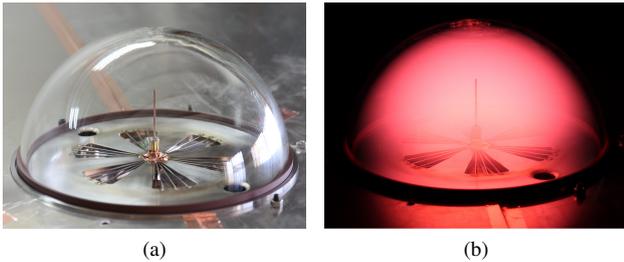


Fig. 2. Pictures of the plasma-based antenna (a) without plasma and (b) with plasma [12].

at 50 cm from the center of the antenna on the ground plane. Compared to the case without plasma, an increase of 20 dB around 300 MHz was measured on the coefficient of transmission. The frequency reconfigurability of the antenna has also been observed by modifying the RF power supplied to the plasma. Additional measurements were performed to quantify the radiation performance of the antenna more precisely. These results are currently being synthesized and therefore not presented in detail in this document. Nevertheless, it is important to mention that a maximum gain around 0 dBi has been measured at the operating frequency of the antenna for an omnidirectional radiation pattern.

III. EXPERIMENTAL SETUP

To evaluate the potential electromagnetic hardening properties of the antenna, the method consists in experimentally illuminating it with an ElectroMagnetic Pulse (EMP) while collecting its output voltage on a 50Ω load. Locally similar to a plane wave, the EMP is typically a “double-exponential” but the specific time-domain waveform is classified. However, the frequency spectrum of the EMP is wide enough to induce a significant coupling in the operating band of the antenna. Consequently, the work presented deals only with the peak level of the output voltage of the antenna when it is illuminated with an EMP of a given peak electric field.

In order to cover a wide range of electric field values that can be applied to the antenna, two EMP simulators at CEA, DAM, Gramat have been selected. The first facility is a GTEM cell [17], which is a strip line expanding pyramidally for guiding an electromagnetic wave similar to a TEM wave

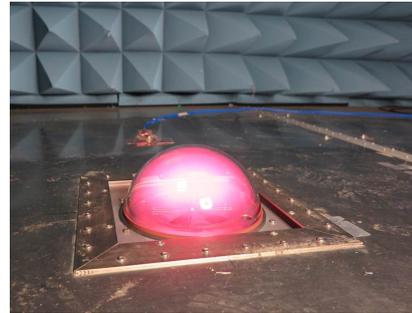
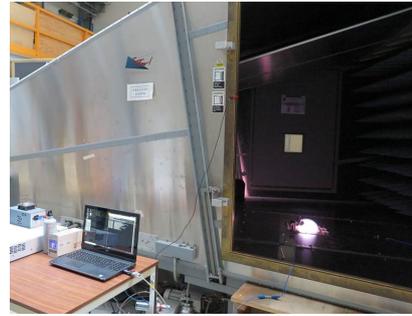


Fig. 3. Pictures of the plasma-based antenna in the GTEM cell.

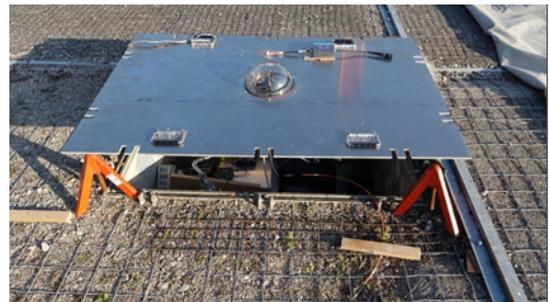


Fig. 4. Pictures of the plasma-based antenna (without plasma) in the high voltage pulse facility. During illumination, the square ground plane is lowered and connected to the facility ground plane.

through the device under test (DUT), namely the antenna. Associated with swappable pulse generators, the GTEM is a versatile way to deliver a maximum electric field of about 40 kV/m at the DUT location. The hemispherical glass shell containing the plasma discharge is set up in the GTEM cell as shown in Fig. 3.

The second experimental facility, presented in Fig. 4, delivers an EMP with a maximum field of up to 120 kV/m at the DUT location. Used as a certification tool for various systems, including vehicles, this larger facility provides a stronger electric field but offers less magnitude adjustability.

Note that these two experimental setups allow to illuminate the plasma antenna without disturbing the operation of the equipment required to maintained the plasma discharge. As visible on Fig. 4, the different devices are placed below the metallic ground plane of both facilities. For both EMP

systems, the incident electric field illuminating the antenna is also measured locally near the antenna using electric field sensors to evaluate the incoming electric field magnitude.

IV. RESULTS AND DISCUSSION

The results are summarized on Fig. 5. The specific time-domain waveform of the EMP used in the GTEM was slightly different than the EMP provided by the high voltage pulse generator. Hence, extrapolation on the results of the GTEM cell was performed in order to compare the two configurations. Since the GTEM operates at a lower level, a linear response of the plasma-based antenna has been assumed for this extrapolation. This assumption is supported by the fact that the obtained levels are still below the voltage collected in the high-level EMP facility. Fig. 5 shows that the results obtained in that second experiment match with the linear fit obtained with the GTEM measurements up to about 70 kV/m. Above this threshold, the output voltage collected by the plasma-based antenna stops growing linearly and seems to be independent of the incident EMP levels. In particular, the collected voltage seems to saturate around a value of 200 V.

To check that this non-linearity is not due to a faulty measurement setup, the high-level EMP coupling was repeated on the plasma-based antenna in the case without plasma. For this configuration, the antenna only consists of a 5 cm long monopole positioned on a ground plane and surrounded by a glass shell. In that case, the high-level EMP no longer couples efficiently with the monopole which theoretically behaves like an electric field sensor with a linear response. This behavior is well and truly observed in experimentation in Fig. 5. To complete this result, numerical studies have also been performed to simulate the illumination of the plasma-based antenna in the case without plasma by the high-level EMP. As shown in Fig. 5, the numerical results are in good agreement with the experimental ones. Note that the measurement chain performing the acquisition of the voltage collected by the antenna is typically used for applications collecting a much higher voltage than those involved in this study. Thus, we assume that the observed effect does not come from a defect of this equipment.

At present, no explanation of the non-linearly behavior of the plasma-based antenna when illuminated by a high-level EMP is validated. However, a hypothesis may be that the incident EMP provides momentary enough power to change the electron density of the plasma discharge. This modification can lead to a shift of the resonant frequency of the sub-wavelength ENG resonator, namely the hemispherical plasma discharge. Thus, two phenomena can occur. First, the coupling between the ENG resonator and the small monopole is less efficient reducing the voltage to the transmission line. Second, if the operating point of the antenna is shifted to a higher frequency, the incident spectral content of the high-level EMP is weaker and, therefore, less voltage is able to be collected by the antenna. These two phenomena can tend to stop the progressive rise of the voltage collected by the antenna. Works to confirm this behavior are still ongoing.

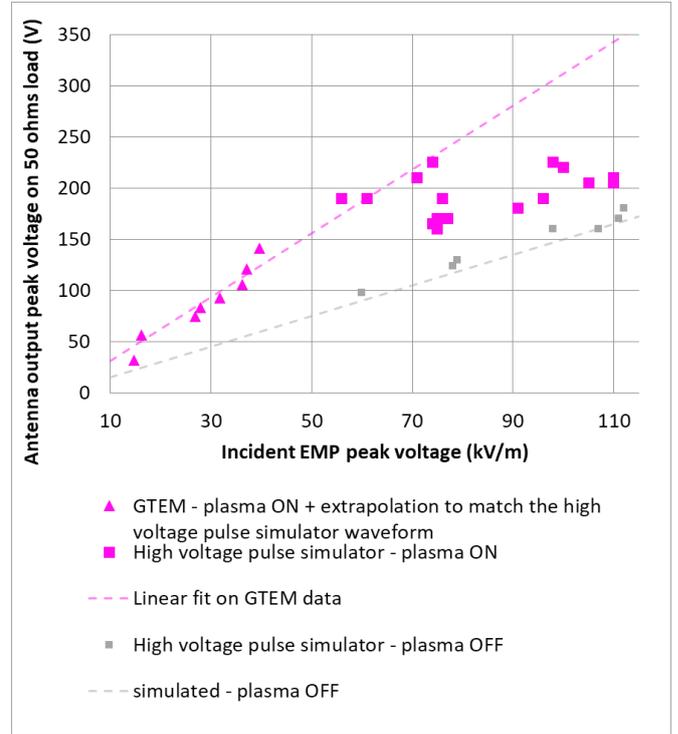


Fig. 5. Antenna output voltage with incident EMP strength. Pink marks for plasma “ON” configurations and gray marks for plasma “OFF” settings.

V. CONCLUSION

Results on a novel kind of antenna based on plasma discharge have been presented. In addition to be electrically small and frequency reconfigurable, this prototype antenna has also shown a non-linear coupling response to an incident high-level EMP. This feature has been explored experimentally in the present work and may be a promising way to limit the stress on the systems connected to the antenna.

The next step will be to better understand and model the non-linear behavior of the plasma-based antenna in order to optimize this feature and/or extrapolate it to various other electromagnetic threats.

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