Electric and Magnetic Antennas as REAL Transmission Lines in Plasma and the Miracle of Self - Focusing of Whistler Mode Propagation

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Abstract

When one considers the losses in an antenna impedance measurement of the Very-low Frequency RPI experiment in space mostly caused by local electrons and ions flowing into the antenna and the spacecraft, instead of radiation, because these losses were non-linear with voltage, and can explain the excellent recordings of multi-bounce whistler mode echoes as self-focused in spite of low power, the search for new antenna configurations is required if high-power transmission is necessary. Understanding the antenna in plasma as a real transmission line, leads to a magnetic-electric antenna, end-loaded with capacity.

1. Introduction

Antenna impedance measurements are extremely important for the antenna design of future high-power experiments in plasma at very low frequencies (VLF). Any modeling and simulation must consider the electron and ion current in the sheath around the antenna.

Near the end of life of the Image satellite radio sounding experiment [1] to monitor the properties of the near plasma and the radio propagation conditions, a program was conceived to study the impedance of the antenna. To accurately measure the capacity of the antenna, a fixed inductor of 22.4 mHy in series with the antenna capacity was chosen and a frequency band of 20 to 40 kHz was scanned. The resonance frequency determined the capacity of the antenna. In addition, the current, provided by the almost constant voltage power supply, was measured.

The voltage on the antenna depends on the losses of the inductor and the antenna losses. In comparing the ratio of the antenna voltage in almost vacuum conditions to those in plasma with the ratio of the power supply currents under those conditions, it became obvious that the voltage decreases much more than the power supply current. While the loss resistor of the inductor is higher at higher currents, the antenna loss resistor, indicated by the current change, increases much less in plasma then it was indicated by the voltage decrease. Thus we have non-linear losses in the antenna. Because the radiation resistor is considered independent of the antenna current and also of the antenna voltage, considering the high Q of the circuit, the antenna has to have non-linear losses in near-field, large compared to the radiation resistor.

It is not necessary to believe that we have to have substantial power to see the beautiful echoes we see in the RPI data. G. Sales [2] has analyzed the probability for the appearance of single and two-hemisphere echoes dependent on the location of the satellite. From this data it is certain that the echo strength does dependent only little on the path length, but substantially on the field strength of the earth magnetic field at the location of the satellite. This proves that the energy of the transmitted extraordinarily polarized signal never leaves the magnetic flux tube in which it was created and the field strength at the receiver antenna depends only on the cross section of the flux tube at the receiver location. Because of this self-focusing, there is not much energy necessary to create good data. But for any application requiring high power at low frequencies, better antennas must be found.

2. The Plasma Sheath around the Electric Antenna

Originally the plasma sheath was defined as the cylinder around the antenna which is devoid of electrons because of the space charge of the antenna. It is the volume which contained before transmission as many electrons as are now charging the antenna. In the RPI antenna test experiment, however, the current source was connected on one side to the antenna and the other side to the huge spacecraft and two smaller and at least one larger antenna. The

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surface for ions getting onto the spacecraft was more than hundred timed larger than the antenna surface. The capacity of the spacecraft was possibly less than ten times smaller than on the antenna. Therefore the AC amplitude on the spacecraft was less than 1/10 of that on the antenna. This resulted in a reduction of the antenna space charge from 97 % to 10% of the peak amplitude on the antenna and a huge increase in local losses. Because it is the volume where the electrons and ions move anti-parallel to the antenna, I want to keep the name: plasma sheath. But I want to extent the sheath far outside the antenna, because electrons and ions can come from far away. Since the electrons move anti-parallel to the antenna at the feed location and at the ends, they have to move everywhere that way. Because the antenna is a capacity, they move the most when the voltage at the antenna is zero. If electrons move perpendicular to the antenna, in phase with the voltage, they are a loss.

The radiation resistance of an electric antenna in plasma is small because a sheath surrounds the antenna. Electrons and ions travel in this sheath, creating a current opposite to the direction of the current in the antenna. Therefore the antenna in plasma can be understood as a transmission line. J. K. Raines [3] treats even the antenna in vacuum as a transmission line with an end resistor Rsv of about 112.5 Ohm. In vacuum, the transmission line has a radius "bv" of 0.18 λ. In his book [4], Raines develops the full concept of an antenna as a transmission line. This concept says that the antenna radiates only from its end.

3. The Transmission Line Antenna Concept

It should be understood that the standing wave on the antenna created by the source is only an interpretation. In reality, the source current creates a wave propagating with the speed of light in vacuum and, depending on the direction of the antenna in respect to the earth magnetic field, in plasma with the speed of the plasma vacuum speed or faster. At the end of the antenna, the current returns in vacuum as displacement current and in plasma as a real current. In plasma, the sheath and the antenna forming the transmission line have a radius "b_a" between three and twenty meters, as shown by P. Song et al. [1]. In plasma, most of the energy travels along the earth magnetic field line in the whistler mode, the k-vector near the Gendrin [5] angle, producing that energy, has a wavelength of the plasma frequency in vacuum, for a large range of operating frequencies. For a plasma frequency of 400 kHz, this is 750 meter. Raines [3] derives the resistance "Rsa" at the ends of the transmission line antenna, using Booker's principle of the compliment for a loop antenna and a circular slot antenna:
32 / (ba*pi / 750)^4 or 3.3 MΩ for the sheath radius ba = 3.0. Because the antenna length of 125 m is actually not short compared to the wavelength of 750 m, this value must be translated to a serial resistor at the feed point of the antenna. This results in a very low radiation resistor.

Fortunately the situation is not so bad, because there is an end-effect for every antenna. Although the antenna wire is very thin, the end-effect is substantial in plasma because the electron and the ion currents flowing from the plasma and forming the sheath at the ends have the same direction as the antenna current and can therefore be considered as radiating and calculated by Raines [3] transmission line approach. But the current will certainly be less than that of an antenna without a plasma sheath. The end-effect of an antenna can be used for an optimum design of an electric antenna in plasma. An example of an end-loaded antenna is shown in figure 1.

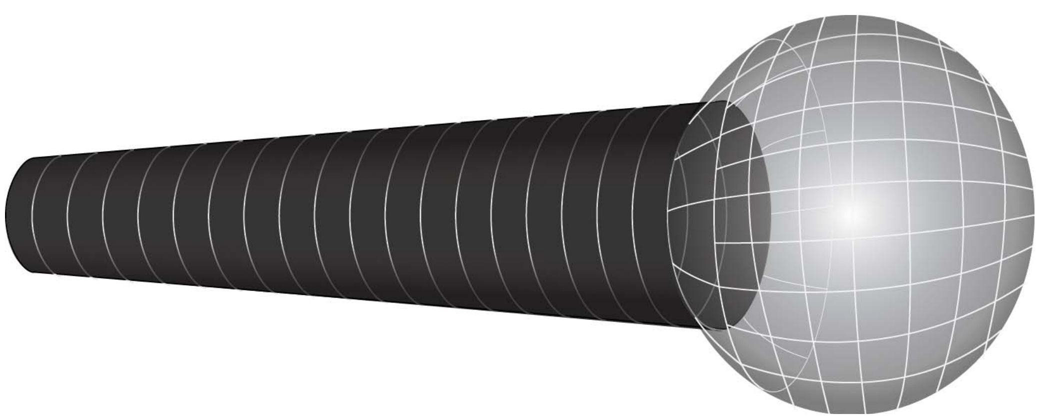

Figure 1. Electric-Magnetic Antenna with Capacitive End-Loading

4. Magnetic Antenna

Because of the severe voltage and radiation resistance limitations of the electric antenna in plasma, a magnetic antenna has been designed using copper bands instead of wire to increase the capacity of adjacent windings increasing the effective inductance without lengthening the total wire length and to reduce the losses. I have shown in laboratory experiments that the wave does not travel along the wire, but uses the capacity between the windings to achieve resonance as a transmission line. The losses in the copper winding are depending on the length of the copper foil. The following formulae are significant for the proposed antenna design. With: b = average coil radius;
s = spacing of copper band; o = overlay of copper band; w = width of copper band;
L = coil inductance; f = transmitted frequency; N = total number of turns;
λn = wavelength of plasma frequency; λ = wavelength in vacuum;
Ro = specific copper resistance; Rr = Radiation resistance; Rc = coil resistance;

$$L = \frac{N^2}{s \cdot N} \cdot (\pi \cdot b)^2 \cdot 4 \cdot \pi \cdot 10^{-7} = \frac{N}{s} \cdot 4 \cdot (\pi \cdot b)^2 \cdot 10^{-7} \quad \text{for: } s*N > 20 \qquad Rc = Ro \cdot 2 \cdot \pi \cdot b \cdot N$$

$$Rr = 20 \cdot (\frac{\lambda}{\lambda ne})^{.5} \cdot N^2 \cdot (\frac{2 \cdot \pi}{\lambda ne})^4 \cdot (\pi \cdot b^2)^2 \qquad \frac{Rr}{\omega \cdot L} = \frac{2.5 \cdot N}{f} \cdot (\frac{\lambda}{\lambda ne})^{.5} \cdot (\frac{2 \cdot \pi}{\lambda ne})^4 \cdot \frac{s \cdot b^2}{\pi} \cdot 10^7$$

$$\frac{Rr}{Rc} = 10 \cdot (\frac{\lambda}{\lambda ne})^{.5} \cdot (\frac{2 \cdot \pi}{\lambda ne})^4 \cdot \pi \cdot b^3 \cdot \frac{w}{Ro}$$

As an example, the results for a magnetic transmitting antenna at 10 kHz are given:
Plasma Frequency fn = 780 kHz; Electron Gyro Frequency fce = 80 kHz; Copper Strip Spacing d = 0.08 m; Overlap o = 0.02 m; width of strip w = 0.10 m; Number of Turns N = 1000; Coil Length Λc = 80 m; Average Inductor Radius 1.6 m; Average Inductor Cross Section S = 8.71 m^2; Total Strip Length T = 10.1 km; Vacuum Wavelength λ = 3*10^8; Group Wavelength in Magnetic Field Direction λg = 3*10^8 * fce / 2*fn*f = 1.5 km; Wavelength in Gendrin angle Direction λk = c/fn = 1.54 km ; Inductance of Magnetic Antenna L = 0.13 Hy; Tuning Capacity Ct = 2010 pf; Antenna Impedance Xl = 7.94 kΩ; Estimated coil Loss Rc = 28.2 Ω; Antenna Current I = 4.0 A; Radiation Resistance Rr = 31.8Ω; Maximum Antenna Voltage Vmax = 31.8 kV; Bandwidth limited by Q = 132; the radiated power would be 508.6 W and the total 959 W for each antenna half. This calculation disregards the losses of the electric components of the antenna.

The magnetic antenna has significant electric radiation. In vacuum it has circular polarization, if the condition: $2\pi b = (2*\lambda n*s)^{.5}$ is met [6]. In plasma a huge end-capacity is required for circular polarization. The ratios Rr / ωL and Rr / Rc show that the radiation would be maximum and the unwanted losses a minimum if the radius of the coil were a maximum. It should be understood, however, that an important purpose of the antenna is that the high voltage part is as far from the spacecraft as possible. Also, a very thick antenna would be difficult to store and expand. It is possible to design a magnetic antenna for 1kW of power for a sufficiently high local plasma frequency.

5. Focusing of Whistler Waves

Encouraged by the report of Stenzel [6] which shows a plane wave and a narrow beam after a limited number of cycles in the direction of the magnetic field, I studied the whistler wave propagation in the direction of the magnetic field. A cross section of the refractive index "n" as a function of the k-vector for whistler waves has a particular W-shape with rounded corners. If the earth magnetic field is perpendicular to the antenna, "n" has a symmetric minimum all around (φ) the magnetic field line at a specific k-vector angle off the magnetic field direction, called Gendrin angle: cos(θg) = 2f / fce, where f is the transmitting frequency, fn is the plasma frequency, and fce is the electron gyro frequency. Developing Booker□s [7] formula for Whistler propagation in magnetic field direction:

$$\frac{Ull}{c} = \frac{fce}{fn} \cdot \frac{fce}{2 \cdot f \cdot (1+\varepsilon)} \cdot \frac{f}{fce} \cdot [\frac{2 \cdot f \cdot (1+\varepsilon)}{fce} - \frac{f}{fce}]^{.5}] \cdot [1 + \frac{2 \cdot f \cdot (1+\varepsilon)}{fce} \cdot (\frac{2 \cdot f \cdot (1+\varepsilon)}{fce} - \frac{2 \cdot f}{fce})]$$

$$\frac{Ull}{c} = \frac{fce}{2 \cdot fn} \cdot [1 - \frac{(1-2 \cdot \varepsilon)^{.5}}{1-\varepsilon}] \cdot [1 + (\frac{2 \cdot f}{fce})^2 \cdot (1-\varepsilon) \cdot \varepsilon]$$

$$\frac{Ull}{c} = \frac{fce}{2 \cdot fn} \cdot [1 - \frac{(1-2 \cdot \varepsilon)^{.5}}{1-\varepsilon}] \text{ for f<<fce} \qquad \text{For: } \varepsilon = 0.01 \qquad 10000 \cdot [1 - \frac{(1-2 \cdot \varepsilon)^{.5}}{1-\varepsilon}] = 0.51$$

This example shows that, for the propagation in the magnetic field direction, at a transmitted frequency of 30 kHz and a ratio of 1/10 for fce /2*fn and at distance of 5,000 km the speed of a wave launched by the k-vector near the Gendrin angle by + -1% loses only 1/4 of a cycle in a whole circle with a weight of cos^2(φ). Because Ull decreases with increased fn, the wave follows the magnetic field towards the earth.

6. Conclusion

The study of the properties of an actual high voltage antenna in space has led to the conclusion that an electric antenna in space has substantial local losses and requires significant capacities at their ends. The end capacities for antennas in plasma are more important than formerly anticipated, because their effects on radiation are shown to be large when the transmission line model of the antenna is considered. The optimum electric antenna would be insulated, long and thin and terminated by a balloon, covered on the outer half by an insulated net of thin wires.

Because in many application, to avoid high voltages near the spacecraft, it will be difficult to make each antenna half -length close to λ/4. Magnetic antennas can overcome the voltage limitations near the spacecraft and the length limitations at low frequencies. A combination of an electric antenna with end-capacity and a magnetic antenna provides maximum power through circular polarization.

7. References

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