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SPONTANEOUS RADIATION EMITTED BY MOVING TETHERED SYSTEMS

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I will first outline some concepts related to radiation emitted by a large conductor moving through a magnetoplasma and refer them to the case of long tethers. Next, I will show some recent results of a theoretical calculation of Alfven wings, their structure and the power associated with them. I anticipate that these results are different from those foreseen, on the basis of qualitative reasoning by Drell et al. (1965) and that we have understood the reason for this difference.

In Figure 1, I have sketched how the problem of radiation from TSS or, more generally, for any large conductor moving through a magnetoplasma, should be approached. The approach is that of the theory of antennas in plasmas. What I have written is the equation for the space-time Fourier transform of the electric field radiated from the moving conductor with, on the right hand side, the transform of the current on the conductor.

We refer to the case of no pulsation of the current; in other words, we look at the electromagnetic fields emitted just because of the motion. The function $\delta(\omega - u_x V)$ on the right hand side is the effect of such motion, with velocity V in the x direction, and tells us a very important point: only plasma modes whose dispersion relation satisfy the Cerenkov condition

$$\omega = K_x V$$

will be radiated by the moving conductor. In a paper by Belcastro et al. (1982), we have analyzed this relation in the context of cold plasma theory with the conclusions which I have summarized in the viewgraph: 1) in the domain of hydromagnetic frequencies, only Alfven waves and not magnetosonic modes can be radiated. In addition, these Alfven waves have propagation vectors almost perpendicular to the magnetic field. In terms of the angle θ between $\underline{K}$ and $\underline{B}$, the solutions to the Cerenkov condition are

$$\theta_1 = \text{arctangent } \frac{V_A}{V}$$

$$\theta_2 = \pi - \theta_1$$

2) going to higher than hydromagnetic frequencies, it is found that the resonance condition is satisfied only for frequencies close to the three plasma resonance frequencies $W_{1\infty}$, $W_{2\infty}$, and $W_{3\infty}$ which are the frequencies where the index of refraction goes to infinity. For the case of parallel propagation, these three frequencies correspond to the ion cyclotron frequency, the electron cyclotron frequency and the electron plasma frequency, respectively. They do, however, vary with the angle of propagation, and in Figure 2 I have shown the corresponding variations. For example, we see that $W_{2\infty}$, going from parallel to perpendicular propagation, goes from the electron cyclotron frequency to the lower hybrid frequency and therefore covers essentially all the whistler range. In any case, this shows the range of possible frequencies radiated by a given moving conductor in a plasma as a consequence of the Cerenkov radiation condition.

There are actually other limitations to the frequencies emitted which have to do with the dimensions of the conductor transverse to the direction of motion. This is shown in Figure 3. The potential difference across the conductor is applied for a time

$$T \sim \frac{D}{V}$$

equal to the time the conductor takes to cross its dimension D perpendicular to its direction of motion. The inverse of this time

$$f^* \sim \frac{1}{T}$$

is clearly an upper limit to the frequencies of the electromagnetic perturbations emitted by the conductor (in the sense that there will be no significant power emitted for frequencies $f > f^*$). Thus, we see that, in order to have a pure hydromagnetic perturbation associated with the conductor, we need

$$f^* < f_{ci}$$

and, hence, very large conductor dimensions

$$D \geq 40 \text{ meters}$$

This is not the case for TSS and, indeed, the electromagnetic perturbation associated with TSS will be something more complicated than pure Alfven waves. For TSS, if we take as a reference the satellite dimensions (D = 1.2m) we get

$$f^* \sim 6.6 \text{ kHz}$$

which falls in the whistler range.

After precising these concepts related to the frequencies emitted by TSS, let me show results of a formal calculation of the Alfven wave radiation emitted by a large conductor (Dobrowolny and Veltri, 1985).

Figure 4 reports first of all our results for the power radiated in Alfven waves.

As applied to TSS, this gives, for a tether length L = 100 km and a current I = 1 ampere, only a few watts of power. The point that I want to bring, however, is that this calculated power is different from that estimated early by Drell et al.(1965) which I have written in the next line of the viewgraph. What we find is precisely a factor $(V/V_A)^2$ smaller which is a considerable reduction. I think we understand now the reason of the difference and that our result is right and I would like to explain that.

In the remaining part of the figure I am showing the way Drell et al. did their estimate and the conceptual mistake which is hidden there. Drell et al. estimated power from

$$P \sim \frac{\delta B^2}{8\pi} \quad V_A S$$

Here it is supposed that an alfvenic perturbation δB is propagating with velocity V_A along magnetic field lines. The formula is all right provided that one uses in there the correct estimate for δB. To arrive at their result, Drell et al. used

$$\delta B \sim \frac{I}{D}$$

which, as you see, is the field associated with a constant current (in the magnetic field direction). Now, there is such a field and there is power associated with it, but that happens just because the current is moving; and it is moving not with the velocity of V_A but the conductor's velocity V and not in the magnetic field direction, but in the direction of motion. If we use this δB in the estimated power, we have to multiply the corresponding energy not by $V_A S$ but by

$$\underline{V} \cdot \underline{S} = V \frac{V}{V_A} S$$

so that we end up with a factor $\left(\frac{V}{V_A}\right)^2$ of reduction with respect to Drell et al.

On the other hand, we can use the above formula for estimating power provided we use there not the δB of the constant current but the δB_A of the alfvenic perturbation. Now it can be seen very easily that

$$\delta B_A \sim \frac{K_{\parallel}}{K_{\perp}} \delta B \sim \frac{V}{V_A} \delta B$$

where the last inequality is due to the Cerenkov condition that was discussed before. If we use this expression we end up with our formal result.

Thus the power spontaneously radiated in Alfven waves is of the order of 1 watt. But, remember that that is not the only power emitted by the tether. There is power in higher frequencies as well. Besides, nobody has looked yet at warm plasma phenomena and, for example, on how much power is emitted in Bernstein modes from the tether.

References

1. S. D. Drell, H. M. Foley, M. A. Ruderman, J. Geophys. Res 70, 3131, 1965.

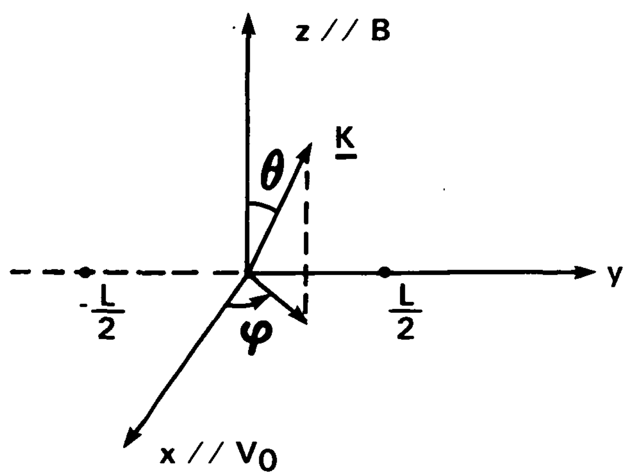
2. V. Belcestro, P. Veltri, M. Dobrowolny, Il Nuovo Cincento C 5, 537, 1982.

3. M. Dobrowolny, P. Veltri, to be published in Nuovo Cincento, 1985.

FIGURE 1

Radiation From The Moving Tether

— **Current Source:** $J_0 = J_0\,(x - V_0 t,\ y,\ z)$



— **Radiated Electric Field:**

$$\Lambda_{ij}\left(\underline{K},\omega\right) E_j\left(\underline{K},\omega\right) = -\frac{i}{\omega}\,\delta\left(\omega - K_x V_0\right) J_{0i}\left(\underline{K}\right)$$

$$\Lambda_{ij} = \eta^2\left(x_i x_j - \delta_{ij}\right) - \epsilon_{ij}$$

$\det \Lambda_{ij} = 0$ ⟶ **Dispersion Relation**

— **Resonance Condition:**

$\omega = k_x V_0$ or $\eta\left(\omega, \theta, \varphi\right) = \dfrac{C}{V_0 \sin\theta \cos\varphi}$

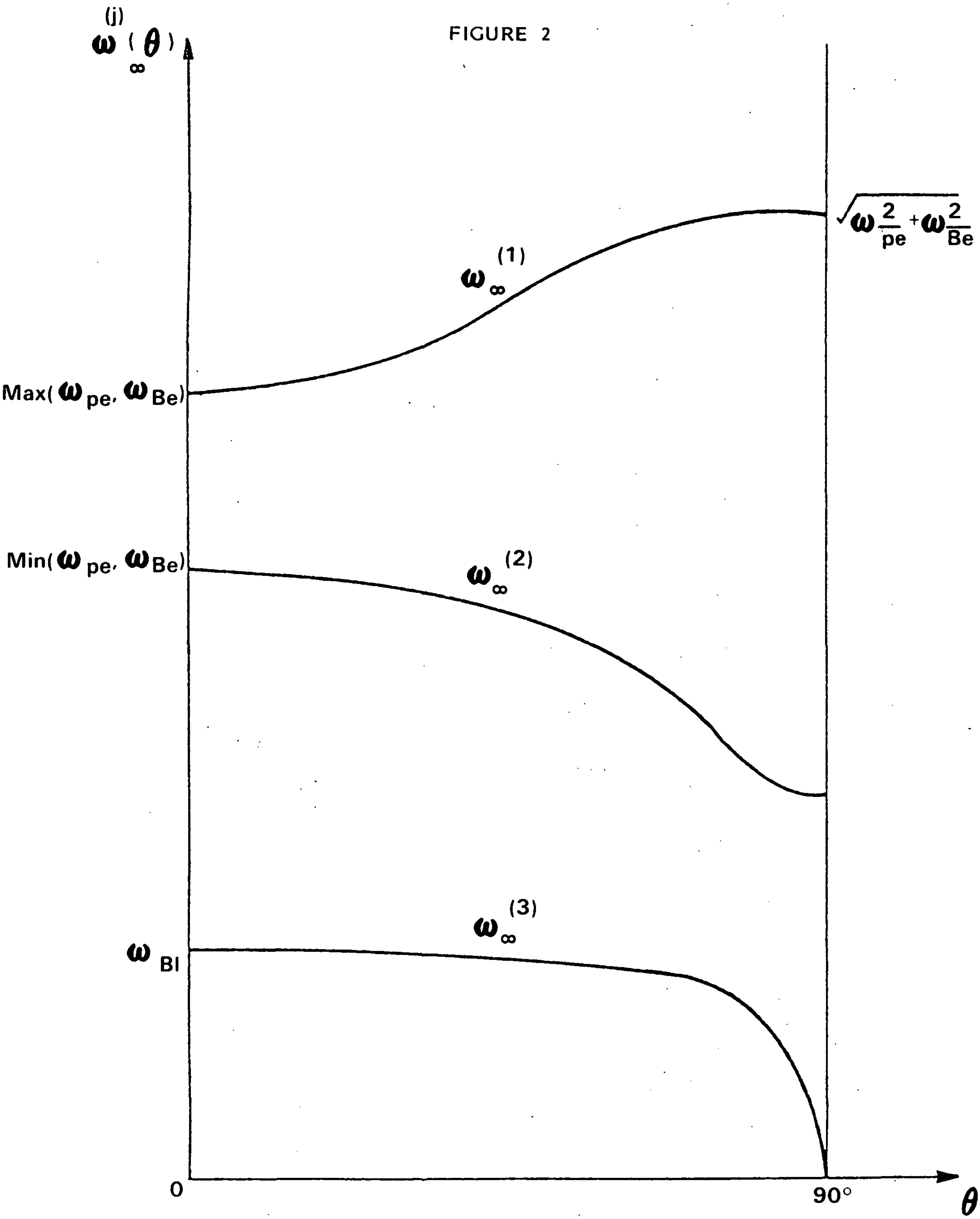
— **Radiated Modes:**

Alfven Waves for $\omega < \Omega_{ci}$ $\left(\theta = \arctan \dfrac{V_A}{V}\right)$

Quasi-Longitudinal Waves Near Resonant Frequencies

$\left(\Omega_{ci}, \Omega_{ce}, \omega_{pe}\right)$

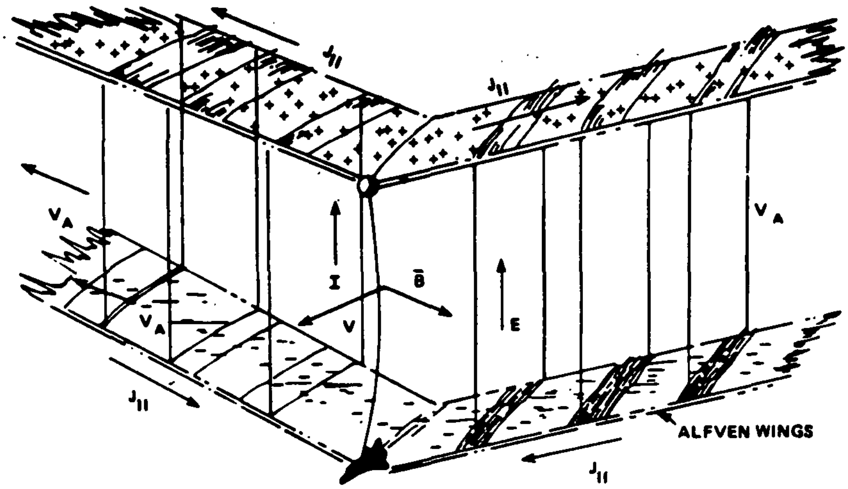
FIGURE 2



$\omega_\infty^{(j)}(\theta)$
$\sqrt{\omega_{pe}^2+\omega_{Be}^2}$
$\omega_\infty^{(1)}$
Max(ω_{pe}, ω_{Be})
Min(ω_{pe}, ω_{Be})
$\omega_\infty^{(2)}$
$\omega_\infty^{(3)}$
ω_{Bl}
0
90°
θ

FIGURE 3

Perturbation Induced By TSS In The Ionosphere



$$\tau \sim \frac{D}{V}$$

$$f \lesssim f^* \sim \frac{1}{\tau}$$

To have only AW radiated:

$f^* < f_{ci}$ ⟶ $D \gtrsim 40m$

for TSS satellite (D = 1.2m):

$f^* \sim 6.6$ KHz

FIGURE 4

Power Radiated By TSS In Alfven Waves

Belcestro, Dobrowolny, Veltri, 1982

Dobrowolny, Veltri, 1985

$$P_{AW} \simeq \frac{V_A}{C^2} \frac{L}{D} \left(\frac{V_0}{V_A}\right)^2 I^2 \qquad = \left(\frac{V_0}{V_A}\right)^2 P_{DFR}$$

from early estimates of Drell, Foley, Ruderman:

$$P_{DFR} = \frac{V_A}{C^2} \frac{L}{D} I^2$$

$$P_{DFR} \sim \frac{\delta B^2}{8\pi} V_A S$$

$$\delta B \sim \frac{I}{D}$$ (field associated with dc current)

this field is moving with volocity V (not V_A) and not in the magnetic field direction

— Alfvenic field $$\delta B_A \sim \frac{K_{\parallel}}{K_{\perp}} \delta B \sim \frac{V}{V_A} \delta B$$

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for $L \sim 100$ km $\qquad I = 1$ ampere

$\longrightarrow$ $P_{AW} \sim 1$ watt