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NOTE ON THE USE OF CHARGE INJECTION FOR SGEMP SIMULATION

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This note discusses techniques and rationale for using self-contained electrical pulsers for simulating system-generated electromagnetic pulse (SGEMP) generated by X rays striking satellites.

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1. INTRODUCTION

Carleton Jones and his colleagues at Pulsar Associates, Inc., have demonstrated the feasibility of constructing small, self-contained electrical pulsers with very fast rise rates. The Pulsar effort, supported by the Defense Nuclear Agency, is part of a program aimed at simulating the electrical effects of photoelectrons ejected from structures in vacuum.

The present note, which was stimulated by a briefing given by Pulsar personnel at a DNA sponsored meeting, discusses some of the basic physics involved in the use of such pulsers for simulation.

The pulsers can be used in two different ways: first, to inject currents directly in structual members; second, to displace charge from a surface to a point in space outside the surface. The second use would appear to simulate more closely the effects of photoelectrons, and it is this type of use that we shall consider here.

2. BASIC IDEA

The basic idea behind the Pulsar effort is illustrated in its simplest form in Figure 1. Enclosed in a metal container, here idealized as spherical, is a capacitor, a switch, an inductance (which may be just the unavoidable inductance) and resistances as shown. The capacitance is initially charged with the sign indicated to a voltage V. When the switch is closed, positive charge flows along the wire and spreads out on the conducting wall. An equal amount of negative charge flows through the hole onto the outer surface of the sphere. Externally it appears that negative charge is moved from the conducting wall to the sphere surface; thus simulating the motion of photoelectrons to some degree. Eventually the charge will leak off through the resistance R_0, and it will appear externally that the negative charge on the sphere surface has returned to the conducting wall.

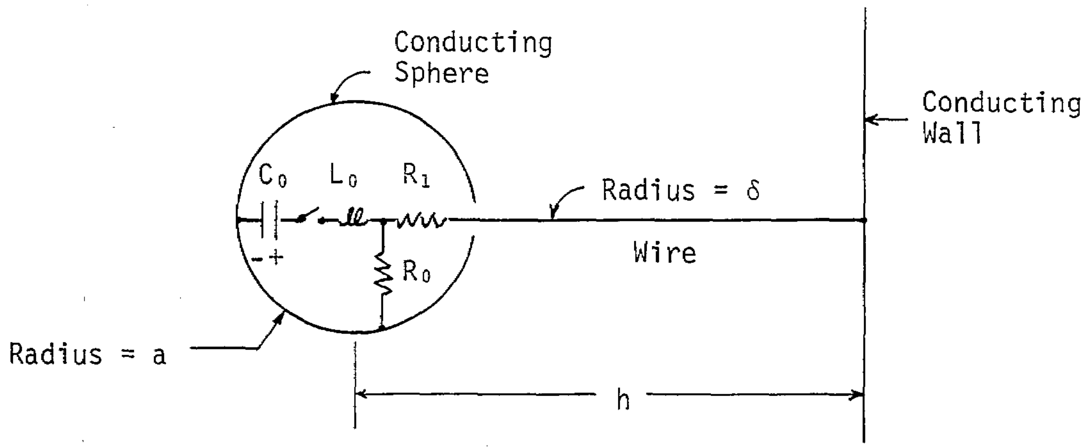

Figure 1. Basic scheme for use of self-contained pulser.

The rise time of the external charge on the sphere is interesting; it should be about equal to the transit time of photoelectrons from wall to sphere. We shall estimate the rise time on the assumption that the capacitance C_0 is large compared to the capacitance C_1 between sphere and wall, that $R_1 >> R_0$, and that the inductance L_0 and the inductance of the wire are negligible. The equivalent circuit is shown in Figure 2. The rise time T_r of the charge on C_1 is then approximately

$$T_r \approx R_1 C_1 \ . \tag{1}$$

If the sphere is not too close to the wall, the capacitance C_1 is approximately

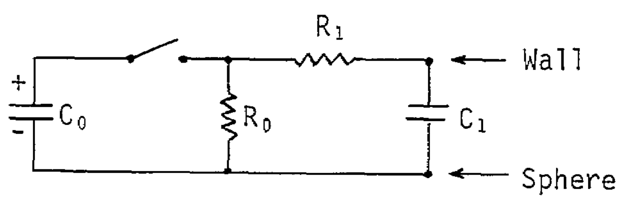

Figure 2. Approximate equivalent circuit for Figure 1.

$$C_1(\mathrm{pf}) = 1.11\, a\,(\mathrm{cm}) \,, \tag{2}$$

where a is the radius of the sphere. Thus we have

$$T_r(\mathrm{sec}) = 1.11 \times 10^{-12}\, a R_1(\mathrm{ohms}) \,. \tag{3}$$

The transit time T_e of photoelectrons is

$$T_e = \frac{h}{v} = \frac{h}{c}\frac{c}{v} = 3.33 \times 10^{-11}\, \frac{h}{\beta} \,, \tag{4}$$

where h is the distance from the wall, v is the velocity of the electrons, c is the velocity of light, and

$$\beta \equiv \frac{v}{c} \approx 0.1 \,. \tag{5}$$

Therefore T_r and T_e will be equal if

$$\left.\begin{aligned} R_1(\mathrm{ohms}) &= 30\,\frac{h}{a\beta} \,, \\ &= 300\,\frac{h}{a}\ (\beta = 0.1) \,. \end{aligned}\right\} \tag{6}$$

We need to check that the inductance of the wire is negligible. This inductance is approximately

$$L(\mathrm{nh}) = 2\left[\ln\left(\frac{h}{\delta}\right)\right] h(\mathrm{cm}) \,, \tag{7}$$

where δ is the radius of the wire. The inductance will be negligible if

$$\frac{L}{R_1} << T_r \,. \tag{8}$$

With the help of Equations 3, 6 and 7, this condition may be written as

$$\left.\begin{aligned} \ln\left(\frac{h}{\delta}\right) &<< \frac{1}{2\beta^2}\,\frac{h}{a} \,, \\ &<< 50\,\frac{h}{a}\ (\beta = 0.1) \,. \end{aligned}\right\} \tag{9}$$

This condition obviously allows the use of very fine wire (small δ), which will be desirable for reasons to be considered below.

Thus we see, from Equations 6 and 9, that parameters can easily be chosen to achieve the desired rise time. Similarly, the decay time R_0C_0 can be chosen to have the desired value, which is in fact comparable with the rise time. Since we have assumed $C_0 \gg C_1$, we will need $R_0 \ll R_1$, which agrees with the approximations made above.

3. GENERALIZATIONS: I

There are several obvious generalizations of the basic idea. A simple and important one is shown in Figure 3, where an additional wire is connected, through a resistance R_2, to a different point on the conducting wall. The purpose is to cause some of the negative charge removed from the surface to return to it at a different point. The equivalent circuit for this arrangement is shown in Figure 4. Again we assume that $C_0 \gg C_1$, $R_0 \ll R_1$. Then the voltage that appears at the point A will be approximately the exponential trigger

$$V_A(t) = V_0 e^{-\gamma t} \quad (t > 0) \ , \tag{10}$$

where

$$\gamma = (R_0C_0)^{-1} \ , \tag{11}$$

and V_0 is the initial voltage on C_0. It is convenient to define two other rate constants

$$\alpha_1 = (R_2C_1)^{-1} \ , \tag{12}$$

$$\alpha_2 = (R'C_1)^{-1} \ , \quad R' = \frac{R_1R_2}{R_1 + R_2} \ . \tag{13}$$

By standard circuit theory one can find the currents I_1 and I_2 flowing through the resistors R_1 and R_2 respectively, or through the two wires,

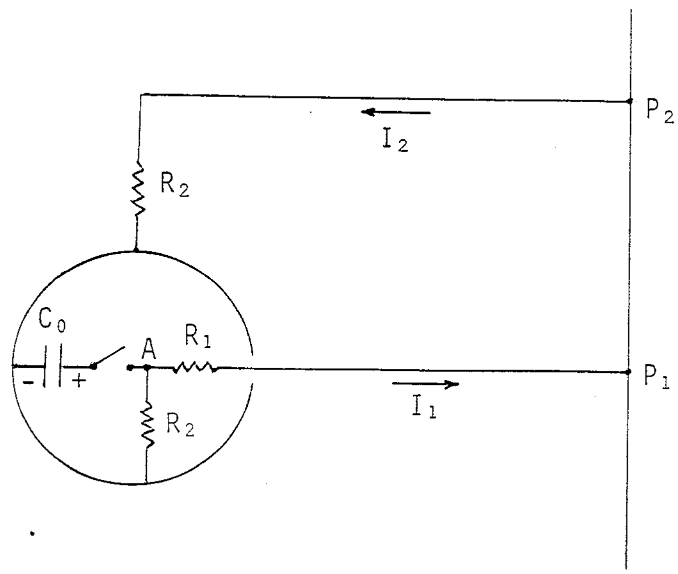

Figure 3. Modification I of basic scheme.

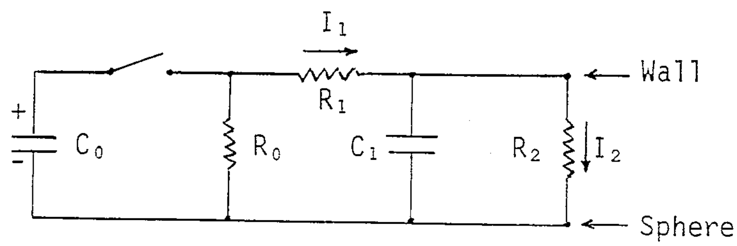

Figure 4. Equivalent circuit for modification I.

$$I_1(t) = \frac{V_0}{R_1}\left\{\frac{(\alpha_1 - \gamma)}{(\alpha_2 - \gamma)} e^{-\gamma t} + \frac{(\alpha_2 - \alpha_1)}{(\alpha_2 - \gamma)} e^{-\alpha_2 t}\right\} , \qquad (14)$$

$$I_2(t) = \frac{V_0}{R_2}\frac{(\alpha_2 - \alpha_1)}{(\alpha_2 - \gamma)}\left\{e^{-\gamma t} - e^{-\alpha_2 t}\right\} . \qquad (15)$$

Note that the positive directions of these currents have been defined such that I_1 is toward the wall whereas I_2 is away from the wall, and that the time integrals of I_1 and I_2 are equal. Note also that the voltage between sphere and wall is I_2R_2.

The rate constants γ, α_1, α_2 can be chosen arbitrarily, except that

$$\frac{\alpha_2}{\alpha_1} = 1 + \frac{R_2}{R_1} > 1 . \qquad (16)$$

This fact insures that I_2 is positive at all times. We may also choose

$$\alpha_2 > \gamma , \qquad (17)$$

which identifies γ with the decay rate, α_2 with the rise rate (the formulae for I_1 and I_2 are symmetrical with respect to interchange of γ and α_2). We can then think of the second term in I_1 (the term in $e^{-\alpha_2 t}$) as representing the initial flow of photoelectrons from wall to sphere. If then we choose

$$\alpha_1 < \gamma , \qquad (18)$$

the first term in I_1 (the term in $e^{-\gamma t}$) can be regarded as the flow of photoelectrons back to the wall over the same path, whereas I_2 is the return flow over the displaced path.

The requirement that inductive effects of the wires be negligible again leads to conditions like Equation 9, which appear to present no serious constraint.

Our assumption that $C_0 >> C_1$, $R_0 << R_1$, which is wasteful of energy stored initially in C_0, is not necessary, but avoids solving cubic equations for the rate constants. Neither alternative appears to present any serious problem.

4. OTHER GENERALIZATIONS

For both of the arrangements discussed thus far, the charge on the sphere (and on the wall) goes to zero at late time. To account for photoelectrons that escape to infinity, it may be desirable to have this charge remain finite. It is easy to achieve this result by adding another capacitor, as in Figure 5. The equivalent circuit is shown in Figure 6. The final voltage V_f between sphere and wall will be

$$V_f = V_0 \frac{C_0}{C_0 + C_1 + C_2} \ . \tag{19}$$

One can easily think of other arrangements, including passive spheres connected through resistors to a driver sphere, or several driver spheres triggered with selected time delays. However, we shall not pursue these ideas here, but rather turn our attention to the quality of simulation available by such techniques.

5. E-FIELD PERTURBATION DUE TO WIRE

The presence of the wire will lead to a reduction of the E-field normal to the wall in the region near the junction of the wire with the wall. If we introduce cylindrical coordinates r, z with the center of the wire as axis r = 0 and z the distance from the wall, then the potential function ϕ near the base of the wire will be approximately of the form (A is a constant)

$$\phi \approx - A\, z\, \ell n\left(\frac{r}{\delta}\right) \ . \tag{20}$$

The potential is zero at the wall $z = 0$ and at the wire radius $r = \delta$. The component of electric field normal to the wall is

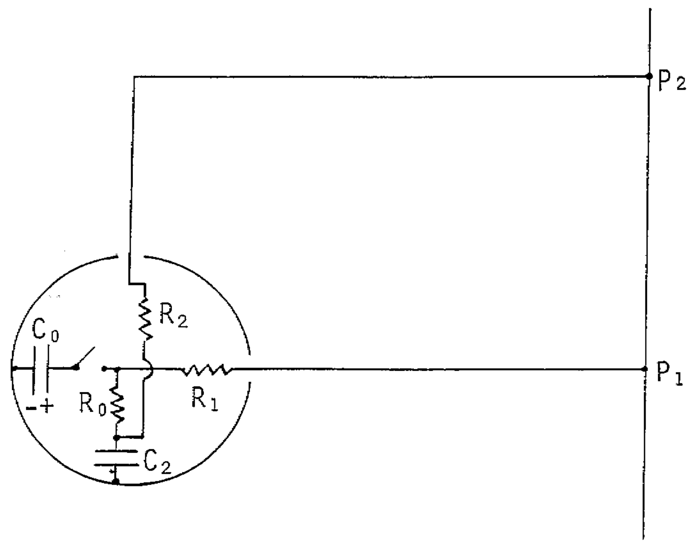

Figure 5. Modification II of basic scheme.

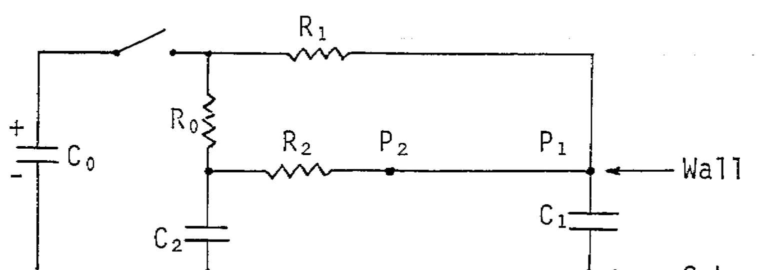

Figure 6. Equivalent circuit of modification II.

$$E_z = -\frac{\partial \phi}{\partial z} \approx A \ell n\left(\frac{r}{\delta}\right) . \tag{21}$$

This field is zero at the wire radius, increases rapidly with r at first, but varies only slowly with r when $r >> \delta$. We choose the normalization factor A to give the correct field E_0 at $r = h$, the height of the wire. Then

$$E_z = E_0 \frac{\ell n(r/\delta)}{\ell n(h/\delta)} . \tag{22}$$

Now suppose we have

$$\left.\begin{aligned} h &= 100 \text{ cm} , \\ \delta &\doteq 0.01 \text{ cm } (\approx 8 \text{ mil diameter}) . \end{aligned}\right\} \tag{23}$$

Then at $r = h$, we have $E_z = E_0$ (by normalization), whereas

$$\left.\begin{aligned} E_z &= \frac{1}{2} E_0 \quad \text{at} \quad r = 1 \text{ cm} , \\ &= \frac{3}{4} E_0 \quad \text{at} \quad r = 10 \text{ cm} , \end{aligned}\right\} \tag{24}$$

Thus we see the importance of keeping the wire radius small. Balance must be made between keeping the wire inductance small, Equation 9, and reducing the area of E-field perturbation.

The wire also increases the capacitance between sphere and wall. The increase in capacitance is kept small by using small δ and by making the hole in the sphere, through which the wire emerges, not too small.

The importance of having the correct normal E-field will vary over the satellite structure, depending on whether the local circuitry is such as to be excited by E-field coupling. For example, an aperture or a wire above the conducting wall could be so excited.

6. B-FIELD PERTURBATION DUE TO WIRE

Another effect of the wire is to make an abnormally high surface current in the conducting wall near the wire or, equivalently, an abnormally high magnetic field just outside the wall. The only way to reduce this error would be to have many wires connected to many points. Such a procedure would increase the area of abnormally low E-field. However, since the area of substantially depressed E-field can be only a circle of radius $\approx$ 1 cm, it would appear better to use many contact points. These points should be chosen so as to minimize the effect of the E- and B-field perturbations on the electronic circuitry.

We suggest that the multipoint connection be made by bringing a single wire from the pulser to a point near the wall, where it is tied to a compound crow's-foot arrangement, as illustrated in Figure 7.

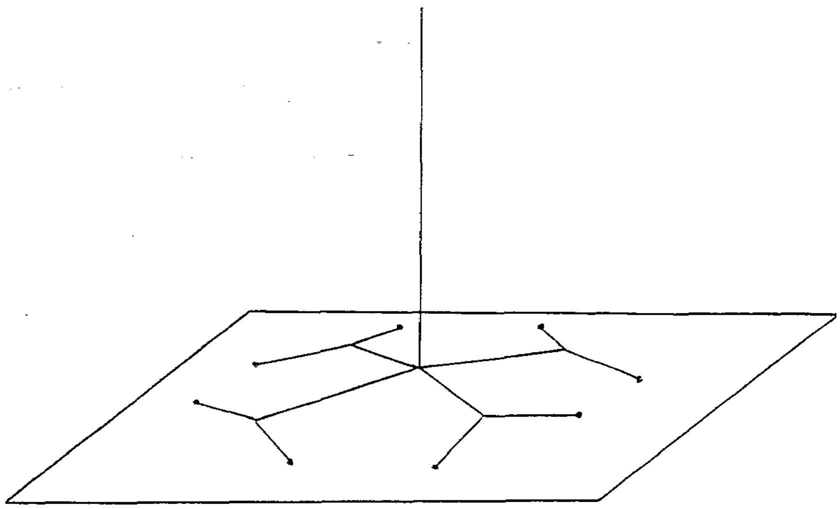

Figure 7. Arrangement for multipoint connection.

7. EFFECT OF WALL IMPEDANCE

Thus far we have neglected any opposition to the flow of current in the wall, as if it were a continuous conducting sheet. (In this case the inductance of this part of the circuit is included in the estimate Equation 7 of the wire inductance.) Due to convoluted structure, the satellite surface may have additional impedance. However, for the metallic part of the structure, this impedance is likely to be quite small compared with the resistance R_1 as determined by Equation 6, particularly if the ratio h/a is sizable, say of the order of 10. Thus we need not worry about the surface impedance having an appreciable effect on the current pulse amplitude or shape.

In order to assure proper distribution of current over the crow's foot, resistances could be used in it, as long as they are kept small in volume.

8. HANDLING OF INSULATORS

Photoelectron emission from an insulating surface can be simulated by tying the wire from the pulser to a screen or grid which has been taped to the insulating surface. This grid should not be connected electrically to the metal parts of the satellite structure.

9. EFFECTS ON SATELLITE MODES

The frequencies and field patterns of the satellite natural modes will be shifted by the presence of the additional structure, and additional modes will be introduced in which charges oscillate from satellite to sphere. The shifts in frequency of the natural modes will be small if the radius of the sphere is small compared with the satellite dimensions and if the resistance R_1 is large compared with 377 ohms. Prediction of the frequency shifts is difficult, but they could be determined experimentally. The additional modes should be over-critically damped with the parameters chosen above; in fact, these modes have to do with the rise and decay of charge on the sphere as calculated in earlier sections.

The presence of photoelectrons in space around a satellite also shifts the natural modes, but not, of course, in the same way as our additional structure.

10. GENERAL PHILOSOPHY OF CHARGE INJECTION SIMULATION

The utility of simulation by techniques outlined above is based on the assumption:

I. We assume that we know where and in what quantities photoelectrons are generated, and where they go.

The information assumed here is most easily obtainable in low-fluence cases, where reaction of the fields on photoelectron motions is a small effect. Even in this case:

II. The quality of the simulation is limited by the level of detail to which we are willing to calculate and experimentally inject charge for an actual satellite.

Let us first visualize an experiment in which charge is injected only into the major structural elements of the satellite, and no attempt is made to inject into the electrical circuitry. Then by measuring currents at various places in the circuitry, one can determine the extent to which structural currents transfer to the circuitry. While this transfer is by no means the whole of the SGEMP problem, it is a significant part of the problem, and a part which would be very difficult to handle adequately by calculations alone. This writer believes such experiments could have great value, even though only part of the SGEMP phenomena are simulated.

What data should one take, and how could it be used in addressing the real SGEMP problem? At this point we can make only some suggestions for a way to proceed.

A. Pretest Analysis

a. Divide exterior satellite surface into elements, based on geometry and possible exposed/shaded areas.

b. Identify a set of points for measurement of structural currents, so chosen as to give a reasonably complete description of structural currents.

c. Identify a set of points for measurement of currents in electrical circuitry, so chosen as to relate most directly to malfunction susceptibilities, e.g., at entry points of electronic packages. Some other points may be chosen to aid understanding of transfer from structure to circuits.

B. Single Element Tests

a. Connect wire and crow's foot to a single surface element and place sphere several satellite diameters away, in direction photoelectrons would predominantly move.

b. Use circuit of Figure 1 with $R_0 = \infty$, so that charge removed does not return, simulating escape to infinity.

c. Measure structural currents, and analyze for satellite modes plus quasi-static response. Vary rise time. Is quasi-static response dominant?

d. Measure circuit currents. Note larger or more critical current points. Do circuit currents correlate with structural currents as drive element is varied? If so, establish transfer relations between structural and circuit currents. If not, will have to relate circuit currents to drive currents.

e. Make R_0 finite. Repeat c and d to find dependence on decay time.

f. Reduce length h of wire. Repeat c and d to find dependence on h.

C. Two Element Tests

a. Use circuit of Figure 3 to move charge from one surface element to another.

b. Repeat measurements and analysis of Section B, c and d.

c. Vary rise and decay times, and look for dependences.

D. Use of Results

a. Even general magnitudes of circuit currents, relative to drive currents, are interesting since they can be used to make first-order predictions of malfunction levels. These transfer currents should be compared with estimates of currents induced by X rays striking wires directly, to see which is dominant.

b. Assuming linearity, circuit currents for simulataneous drive of several surface elements will be sum of currents, with proper time phasing, for individual drive.

c. Results would be most useful if the satellite modes could be pulled out of the structure current data, and if the circuit currents correlate with the structure currents. This would mean that the structure provides dominant definition of electromagnetic problem. Then codes need to compute only structural currents, from which circuit currents could be inferred. Also structural currents should be easier to calculate well if we had good understanding of modes.