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TITLE: COMPUTATIONAL SIMULATIONS OF EXPLOSIVE-DRIVEN PLASMA-QUENCH OPENING SWITCHES

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COMPUTATIONAL SIMULATIONS OF EXPLOSIVE DRIVEN PLASMA-QUENCH OPENING SWITCHES

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Summary

High-explosive-driven plasma opening switches have been modeled in one dimension using the Lagrangian MHD code RAVEN. These calculations have been made in both cylindrical and planar geometry. Simple compression can account for observed resistance increases at early times (time-of-flight of the high-explosive detonation products across the plasma conducting channel). Our results suggest that some improvements in switch performance might be achieved through a judicious choice of gases in the plasma channel and by lowering the pressure in the channel.

Introduction

To optimize the operation of explosive-driven magnetic flux compression generators it is desirable to have a low-inductance, fast opening switch that can interrupt many megamperes of current through a ballast inductor in a fraction of a microsecond. In 1977 Pavlovskii et al.[1] reported on a high explosive driven opening switch with which they achieved a resistance change of 0.2 ohms in 0.45 μs, interrupting a current of 7.3 MA and switching 4 MA into a 30 nH load.

Experimental efforts to examine the "Pavlovskii" switch have been carried out by Turman and Tucker[2] and Turman, Tucker and Skogmo[3] at Sandia National Laboratory and Goforth[4] at the Los Alamos National Laboratory. When working at current densities comparable to or higher than the 0.12 MA/cm used by Pavlovskii et al. these experimentors have seen resistance increases closer to 30 mΩ, again on a 0.5 μs time scale.

There has been one previous attempt to simulate these switches computationally. From his study Baker[5] concludes that simple, 1-D compression of the current-carrying plasma channel, the mechanism suggested by Pavlovskii et al., cannot account for the observed resistance increases.

The Model

The bulk of our effort has also been a one dimensional analysis although we are now extending our effort to two dimensions. Our one-dimensional calculations have been carried out using the 1-D MHD code RAVEN[6] in both cylindrical and planar geometry. RAVEN is a Lagrangian code that uses the Braginskii[7] formalisms for electrical and thermal conductivities.

For this study it was necessary to add to RAVEN a high explosive equation of state. The internal energies and pressures are determined from a burn fraction which is determined from the detonation velocity. For cyclotol, which we used in calculating cylindrical geometries, we used an internal energy of 9.2 x 10^{10} ergs released per gram. For PBX 9501, which we used for planar geometries to simulate the Goforth experiments, we used an internal energy of 1.02 x 10^{11} ergs released per gram. For electrical conductivity of the HE detonation products we used 100 mho/m, a value cited by Pavlovskii et al. For thermal conductivity we used the Spitser formalism assuming the detonation products to be singly ionized. In fact, however, varying the thermal conductivity by a factor of one thousand did not significantly effect our calculated results.

The electrical circuit available in RAVEN at the time of this study is shown in Figure #1. This circuit will not permit us to exactly simulate Pavlovskii's experiment. We can introduce an external load on the parallel circuit leg (L_p), but this inductance will not include the return conductor as it does in Pavlovskii experimental set up.

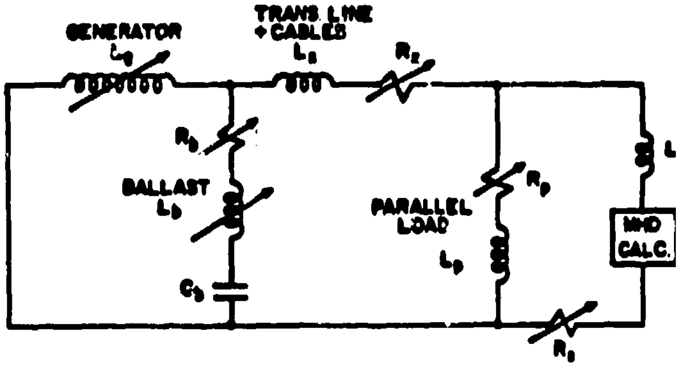

Fig. 1. The electrical circuit available in RAVEN. In our simulations we are using the generator (L_g), the ballast inductor (L_b = 40 nH), the transmission time (L_x = 30 nH), the load inductance (L_l = 1 nH), and the parallel load is used to simulate the alternate current path so that R_b is dropped to zero at peak compression.

We have run cases in both cylindrical and planar geometry. The cylindrical system closely approximates the geometry of Pavlovskii. As is shown in Figure #2, the cylinder has a radius of 12.5 cm. The plasma column has an initial radius of 10 cm and may expand into a 0.5 cm radius gap. The central conductor has a radius of 4 cm. We have taken the cylinder to be 10 cm long. Following the work of Baker[5] we note that after the aluminum foil has vaporized the aluminum represents little more than an impurity in the channel which we, therefore, take to be atmospheric pressure oxygen at 2.5 eV, an arbitrary temperature that is high enough so that the oxygen will conduct. Our planar geometry model is taken from the experimental work of Goforth[4]. It is a 3cm x 3mm cavity that is 5 cm in length.

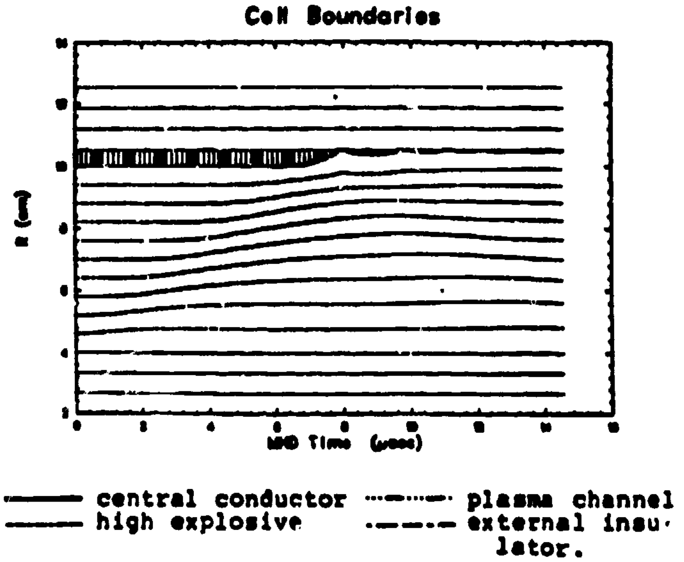

Fig. 2. Radii of each zone in the cylindrical calculation as function of time.

Results

The time behavior of the cylindrical geometry is shown in Figure #2. In these calculations we hold the outer insulator frozen in space. As a consequence, the results of the calculations after the initial compression are certainly not believable. Figure #3 shows a resistance increase that is quite comparable to the initial rises reported by Turman and Tucker. This rise is due solely to the compression of the current carrying channel. During this compression the temperature in the plasma rises sharply to nearly 14 eV and the pressure reaches just over one megabar, a factor of three above the 300 kilobar pressure in the HE.

Our resistance drop is sharper than that in the experimental results of Turman and Tucker. Since the resistivity of the ionized plasma is inversely proportional to the temperature to the 3/2 power this suggests that our calculated temperature increase may occur too rapidly. This would not be surprising since 1-D simulations tend to overestimate temperatures at the peak of compression and our fixed outer insulator may cause an overestimate of the rate of compression.

Our calculated secondary resistance increases are smaller than the first and this does not agree with experiment. In addition, these secondary increases would probably not occur if the outer insulator were free to move. We suspect that later resistance increases are due more to mixing between the hot plasma and relatively cool detonation products than they are to compression. To verify this hypothesis, we are presently carrying out a series of 2-D calculations.

In Figure #4 we show the results for the planar geometry with a current density of 0.22 MA/cm. We initially found this resistance increase, which is higher than that measured by Goforth, rather surprising. Our preliminary analysis indicated that these switches would be stongly limited by current density because the higher current, and subsequent Joule heating, would increase the ionization level of the plasma.

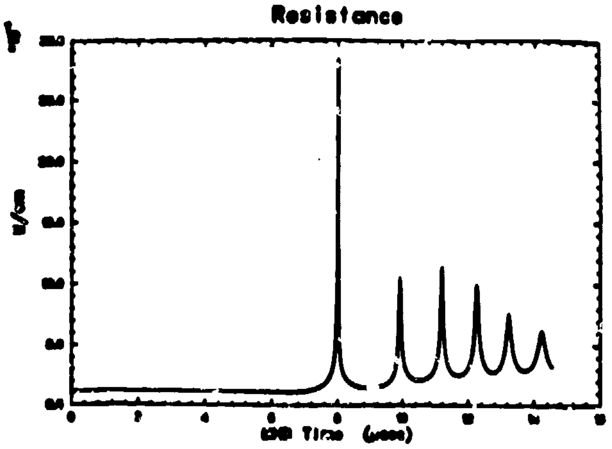

Fig. 3. Calculated resistance along the plasma channel as a function of time for the cylindrical geometry.

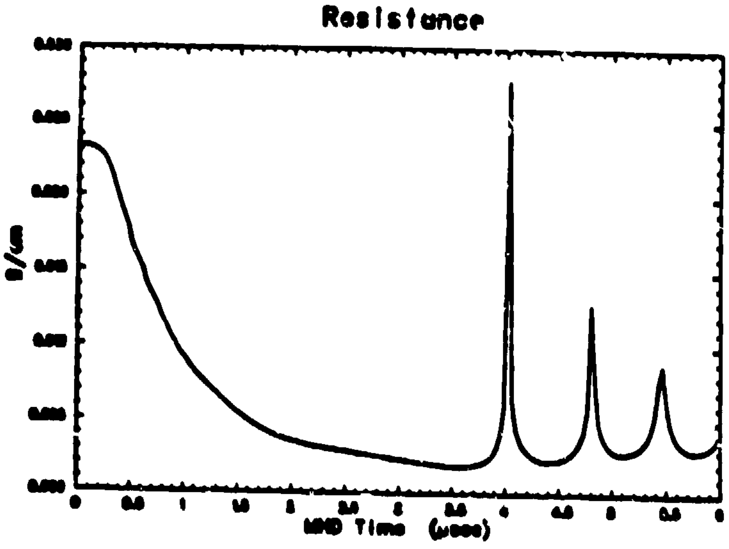

Fig. 4. Calculated resistance along the plasma channel as a function of time for planar geometry.

Analysis and Conclusions

If we are dealing with an ionized plasma ($\bar{Z} > 1$) the resistivity, η, varies as

$$\eta \propto T^{-3/2}$$

If the current carrying plasma is undergoing an adiabatic compression with the ideal gas γ = 5/3, then the cross sectional area will also vary as $T^{-3/2}$. Therefore, since the resistance, R, is just

$$R = \frac{\eta \ell}{A} \tag{1}$$

and, the length, ℓ, does not change, we expect the resistance to be constant during compression once the plasma is ionized.

Figure #5 shows the time behavior of the log of the pressure as a function of density for the planar run of Figure #4. The line plotted during the initial compression shows that we do have an adiabatic compression but the slope is not 1.67 but closer to 1.35. This lower value of γ indicates some sink of energy not included in the above analysis. Additional thought indicates that this sink is likely to be ionization of the oxygen plasma.

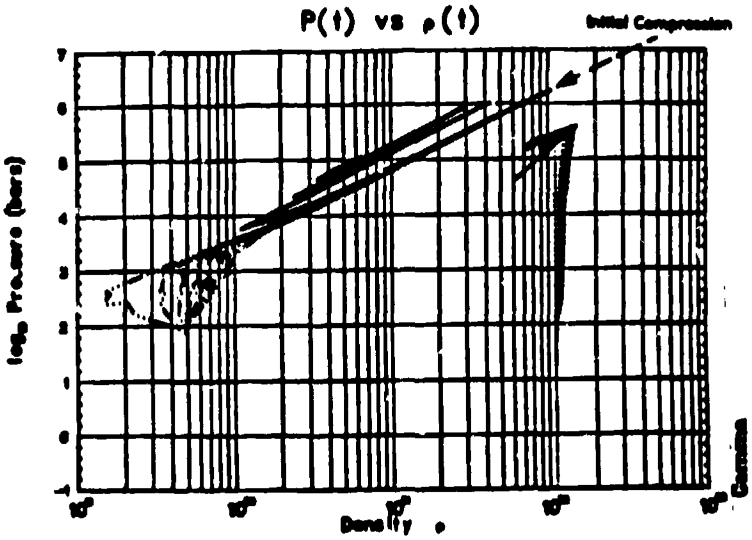

Fig. 5. Pressure vs. density. For a Lagrangian code this is the equivalent of pressure vs $(\text{volume})^{-1}$. Dashed line points to that portion of the plot that was traced during the initial compression.

Armed with this knowledge we can estimate γ based on the level of ionization. The internal energy can be written

$$U = 3/2P + \sum_z \varepsilon_z n_z \tag{2}$$

where ε_z is the sum of the ionization energies up to level z and n_z is the number of ions in level z. We note, however, that we can write pressure as

$$P = (\gamma - 1)U/V \tag{3}$$

where V is the volume. Simple substitution yields

$$\gamma = 1 + \frac{2}{3}\,\frac{1}{1 + \frac{2}{3}\frac{\Sigma \varepsilon_z n_z}{(n_i + n_e)kT}} \tag{4}$$

where n_i is the total ion population and we have substituted in

$$P = (n_i + n_e)\,kT \tag{5}$$

Then, in terms of $\bar{Z}$

$$\gamma = 1 + \frac{2}{3}\,\frac{1}{1 + \frac{2}{3}\frac{\Sigma \varepsilon_z (n_z/n_i)}{(1+\bar{Z})kT}} \tag{6}$$

In the limits of no energy in ionization ($\varepsilon_z = 0$), or very high temperature, Eq. (6) limits to $\gamma = 5/3$ as it should. Between these limits the Saha equation must be solved based on the density and temperature in the plasma. We have solved the Saha equation iteratively for values of constant temperature and density to find values of n_z and, hence $\bar{Z}$, in oxygen and substituted these values into Eq. (6). The results of these calculations are shown in Figure #6.

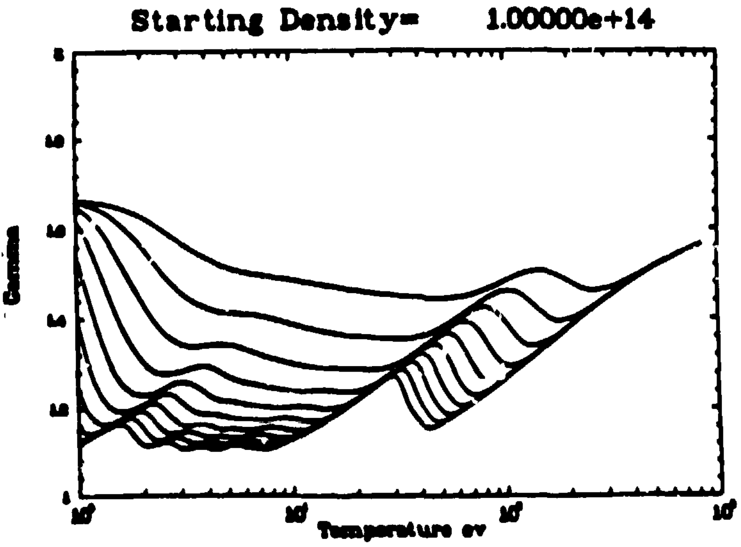

Fig. 6. Gamma as functions of temperature in oxygen. Each line is a factor of ten in density higher than the line below it. The bottom line is an ion density of 10^{14} cm^{-3}, the top line is 10^{23} cm^{-3}.

From Figure #6 we reach three important conclusions. First, it is possible for these switches to be ionized ($\bar{Z} > 1$) and still have $\gamma < 1.67$, so that the resistance can increase, even if weakly, as a function of temperature. This should mean that these switches can be used at higher current densities, and hold these higher current densities for longer times, than we had initially anticipated. This conclusion appears to hold for a very wide range of temperatures. This temperature range is, however, a function of the gas in the plasma. Our second conclusion, therefore, is that something may be gained by carrying out an analysis for a variety of plasma gases in order to determine which gas will provide the best switch.

Finally, we note that although the performance of these switches in the compression regime should be relatively independent of the temperature prior to compression, over a wide temperature range, Figure #6 predicts a strong dependence on pressure or density. This pressure dependence may be the most sensitive parameter available for improving the performance of these switches.

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