LA-UR -83-1609

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE SYSTEM REQUIREMENTS FOR THE LOS ALAMOS FOIL-IMPLOSION PROJECT

AUTHOR(S) J. Brownell, R. Bowers, Greene, I. Lindemuth, G. Nickel, T. Olipha Weiss

SUBMITTED TO Third International Conference on Megagauss Magnetic Field Generation (Novosibirsk, June 12-17, 1983).

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

— Classification —

SYSTEM REQUIREMENTS FOR THE LOS ALAMOS FOIL-IMPLOSION PROJECT

by
J. Brownell, R. Bowers, A. Greene, I. Lindemuth,
G. Nickel, T. Oliphant, D. Weiss

Los Alamos National Laboratory
Los Alamos, New Mexico, U.S.A.

ABSTRACT

The goal of the Los Alamos imploding foil project is the development of an intense source of soft x rays and hot plasma produced from the thermalization of 1-10 MJ of plasma kinetic energy. The source will be used for material studies and fusion experiments. Specifically, thin, current-carrying cylindrical metallic plasmas are imploded via their self-magnetic forces. Features of this project are the use of high-explosive-driven flux-compression generators as the prime power source to achieve very high energies and fast opening switches to shorten the electrical pulses. To reach a load kinetic energy of 10 MJ, it is expected that the foil-plasma must carry about 50 MA of current and must implode in less than 1/2 μsec. This imposes the requirements that switch opening times must be less than 1/2 μsec and the transmission line must withstand voltages of about 1 MV. The system being pursued at Los Alamos is described, and model calculations are presented.

I. Introduction

The goal of the Los Alamos imploding foil project is the development of an intense source of soft x-rays and hot plasma. With an energy content of several megajoules and a time duration of tens of nanoseconds this source will be used for fusion and material properties experiments. To form the source, large currents are passed through thin cylindrical metallic foils producing a plasma that implodes under the action of its self-magnetic force. Upon stagnation on axis a hot, radiative plasma is produced. This concept has been investigated at other laboratories including the Air Force Weapons Laboratory[1,2], Maxwell Laboratories[3], Physics International[4], Sandia National Laboratory[5], and the Kurchatov Institute[6], using capacitor banks. Building from studies carried out jointly by the Air Force Weapons laboratory and Los Alamos National Laboratory in 1975, Los Alamos researchers have proposed to use explosive generators as the prime power source, converting chemical energy to electrical energy.[7]

This paper is intended to describe the presently envisaged Los Alamos system. We will give estimates of the current, voltage and electrical pulse time required to reach megajoule foil kinetic energies and the key issues in operating an explosive generator with an opening switch. The Los Alamos coaxial system is described, including a discussion of the all-important opening switches. Two-dimensional MHD calculations of the component switches are presented.

II. System Requirements

To see how the characteristic quantities scale, we can use a simplified dynamical model: F = ma, where the force, F, is due to the magnetic pressure. If one assumes a constant current and a convergence ratio of 10 for the foil load, the kinetic energy is found to be

$$K.E. \simeq 1/2\Delta L I_f^2 \quad , \tag{1}$$

where I_f is an average current and ΔL is the change in inductance of the foil system during the implosion. For example, for a 2 cm long foil to reach a kinetic energy of 1 MJ with a convergence ratio of 10 it must carry a current of about 15 MA.

Generally speaking, it is desirable to deliver energy to the load and have it implode in as short a time as possible in order to facilitate power flow and minimize the deleterious effects of instabilities and thermal spreading of the plasma on the ultimate power compression. Such considerations have led us to believe that we must not expose the load to current for more than .5 μs.[8]

A possible circuit choice is shown in Fig. 1 where the explosive generator and foil are modeled as time varying inductances. Using existing generators it is found that this circuit can deliver energy to a load on microsecond time scales. The implication is that faster generators must be developed or we must utilize circuits which shorten the electrical energy delivery time. Choices include an inductive storage circuit with a water line or an opening switch. We are examining the latter possiblity.

III. Inductive Storage Circuit

Key issues in operating an MCG circuit with an opening switch can be identified from an analysis of the schematic shown in Fig. 2. The primary reason in going to such a circuit is to achieve a rapid rate of current rise; we note that initially $\frac{dI_2}{dt} \simeq V/L_F$ where V is the voltage across the foil. In addition, it is desired to switch as much of the generator current into the load as possible which requires, first of all, that $R > \dot{L}_F$ at implosion time. For an opening switch which has a sufficiently large R after switching

$$I_2 \simeq \frac{L_{gs} + L_b}{L_g + L_B + L_T + L_F} I_s,$$

where L_{gs} is the generator inductance at the time of switching. To maximize I_2, it is clear that L_T (and L_B) must be minimized. In the limit that $L_T = 0$ the voltage across the switch is the same as that across the foil and K.E. $\propto (I_2)^2_{peak} \propto (V)^2_{peak}$, assuming that the voltage is approximately constant during the implosion. Thus, to maximize both the rate of current rise and the load current, a low impedance tranmission line and a switch that operates at high voltage seems to be needed.

The peak voltage that can be expected to appear across the switch can be estimated from the energy that flows into the imploding foil for $L_T = 0$. This is

$$E = \int_0^t I_2 V\,dt = \langle I_2 \rangle \int_0^t V\,dt. \qquad (2)$$

If the energy is equipartitioned between kinetic and magnetic, then E is twice the desired foil kinetic energy and

$$V_{pk} \approx \frac{4(KE)}{\langle I_2 \rangle\, t_{imp}}$$

where t_{imp} is the foil implosion time. For example, if KE = 1MJ and t_{imp} = 0.5 μs, then $V_p \approx .5$ MV.

IV. Los Alamos System

A. Description

In this section a coaxial system is described which is intended to minimize circuit inductance and avoid power flow problems. A sketch is shown in Fig. 3. Starting from the left a capacitor bank establishes a seed current of 0.5 MA in the Los Alamos MARK IX helical generator, sweeping wave coaxial generator and storage inductor. The MARK IX (similar to the MCG described in Ref. 9) with an initial inductance of about 8 μh and a pulse time of 145 μs acts to boost the system current to about 10 MA. The entrance to the coaxial generator is sealed with an insulator, and it and the rest of the system is evacuated. Upon completion of the MARK IX burn the coaxial sweeping wave starts. This generator has an initial inductance of 100 nh, a pulse time of 100 μs and is internally magnetically insulated.[10] The storage inductance is less than 10 nh. Either near the end of the coaxial generator pulse or after the end when the energy is stored in the inductor, the switch section transfers current through a transmission line into the foil load. The transmission line is magnetically insulated and has a gap width of 1.5 - 2 cm to avoid shorting due to drifting plasma formed by field emission and absorption of ultra-violet light produced by the foil. Note that shortly after the sweeping wave generator has begun its run there is no longer an insulator in the system which should simplify the power flow problem.

B. Current Switch

There are a number of requirements that the switch section in Fig. 4 must satisfy. First of all, it must carry a large current (peaking at several tens of MA) for the duration of the seed capacitor bank discharge plus the burn time of the MARK IX helical generator and the coaxial generator for a total time approaching 400 μs. Secondly, the switch resistance during the burn time of the generators must be less than the $\dot{L}$ of each generator in order to have a positive $\dot{I}$ (e.g. the average $\dot{L}$ of the coaxial generator is about 1 mΩ). Most critically we have the requirement that the switching time must be less the .5 μs. In addition the switch inductance must be very low, and preferably the switch should operate in a vacuum and employ no insulators.

A number of candidates have been examined. To reach the megajoule level, integral switches which use the system current itself to cause opening or commutation hold promise. Two examples that we are examining are the magnetic gate switch proposed by Steinberg and Shearer at the Megagauss I' Conference[11] and the moving plasma switch of Turchi et al.[12] The magswitch with a 10 - 90% risetime of 1.5 μs at a current density of .4 MA/cm and a delay time corresponding to that required by the foil to reach the current diagnostic.[13]

The second class of switches, the moving fluid switches, seems most likely to operate in a commutator mode (though if an anomalous resistivity could be generated in the switch fluid, a breaking action could occur) exciting current in an imploding foil load in a time h/v, where h is the load foil length and v is the switch foil velocity. Transferral of 70% of an initial current has been achieved at Los Alamos with a 10 - 90% risetime of less than 500 ns at a current density of approximately .5 MA/cm.[13] We are also examining plasma gun commutators, and a calculation is given later. These switches have the potential of being very fast and would of necessity have to be used with at least one slower switch. The moving foil could be used, for example, with the more massive gate switch above which would pass current for a long period of time. The closing switch would then close, transferring current to the moving foil switch which would accelerate due to the self-magnetic force. We examine this two-stage cascade below.

C. Two Stage Switch and Kinetic Efficiency

Fig. 4 shows a sketch of a proposed current switching section for the Los Alamos system and Fig. 5 gives the equivalent circuit for the entire system. To determine the ideal fraction of the available energy that is converted to load kinetic energy, the kinetic efficiency, we proceed as follows. Let the generators burn completely (i.e., until $\dot{L}_g = 0$. During this time the gate expands and translates. At burn-out the gate is assumed to either open (i.e., R becomes large) or to commutate the current into the moving fluid switch as the Los Alamos experiments indicate (the analysis is the same); L_{S1} no longer increases and the residual inductance of the generator is included in L_B. Conservation of energy and magnetic flux are then used to determine the system performance.

The energy lost in opening the gate is

$$E_{SW} = \frac{(L_{S2})_1}{L_B+(L_{S1})_1+(L_{S2})_1} E_1$$

where $(L_{S1})_1$ is the gate inductance at switching time, $(L_{S2})_1$ is the commutator inductance at the same time, and E_1 is the initial circuit energy. The expression for E_{SW} makes it clear that it is desirable to have $L \;+ (L\;_1)_1 >> (L\;_2)_1$.

The commutator moves towards the imploding foil and gains the kinetic energy

$$(KE)_c = [L_B + (L_{S1})_1] \frac{[(L_{S2})_2 - (L_{S2})_1]\; E_1}{[L_B + (L_{S1})_1][L_B + (L_{S1})_1 + (L_{S2})_2]}, \quad (3)$$

where $(L_{S2})_2$ is the commutator inductance just before communtation. Commutation then occurs and using the definitions $(L_{S2})_3 = \frac{\mu_0}{2\pi} \ell \ln(\frac{b}{a})$ and $L_F = \frac{\mu}{2\pi} h \ln(\frac{a}{r})$ where $x = 0$ is the furthest point of travel of the gate switch (see Fig. 4), the following expression is found for the kinetic energy of the imploding foil:

$$(KE)_f = \frac{[L_B+(L_{S1})_1][L_{Ff}-L_{F0}]E_1}{[L_B+(L_{S1})_1+(L_{S2})_3+L_{F0}][L_B+(L_{S1})_1+(L_{S2})_3+L_{F0}]} \qquad (4)$$

where L_{F_0} is the initial load inductance and L_{Ff} is the final load inductance. Note that $(L_{S2})_3 = (L_{S2})_2 + \frac{\mu_0}{2\pi} h \ln(\frac{b}{a})$.

Then, given the commutator velocity from the switching time requirement, Eq. (3) gives $(L_{S2})_2$ as a function of $[L_B + (L_{S1})_1]$, E_1, and commutator mass. Eq. (4) then gives the kinetic efficiency, $\eta = (KE)_f/E_1$. For the case where $(L_{S2})_1 = 0$ η is maximized at

$$L_B + (L_{S1})_1 = \frac{\sqrt{L_0 L_1}}{\beta} \quad ,$$

where

$$L_o = \frac{\mu 0}{2\pi} h \ln \left(\frac{b}{r_i}\right) \quad (r_i = \text{initial foil radius}),$$

$$L_i = \frac{\mu_o}{2\pi} h \ln \left(\frac{b}{r_f}\right) \quad (r_f = \text{final foil radius}),$$

and

$$\beta = 1 + \frac{1}{E_i/1/2\ mv^2 - 1} \quad (m = \text{commutator mass},\ v = \text{commutator velocity})$$

As long as E. >> $1/2\ mv^2$, η is maximum at essestially $\sqrt{L_0 L_i}$.The efficiency was found to be rather insensitive to changes in the commutator mass and to be quite high at its peak. Two cases are plotted in Fig. 6.

D. MHD Calculations

We have begun to calculate the behavior of gate switches and commutators using two-dimensional, Eulerian MHD codes which contain the following models:

(i) single-fluid magnetohydrodynamics[14]
(ii) external circuit
(iii) resistivity--solid, liquid vapor, plasma[15]
(iv) equation of state
(v) material strength[16,17,18]

1. Magnetic Gate

Figure 7 shows a preliminary model of a magnetic gate designed to carry the current from the coaxial generator. Two calculations are described here (Table I). The initial current I_0 is 30 MA and $L(t) = L_0 =$ 10 nh. The magnetic pressure resulting from the $\vec{j} \times \vec{B}$ force is balanced by stress gradient in the aluminum until the yield strength is reached if joule heating does not cause melting. During this period the magnetic field diffuses through the gate, and current flows to the load.

Model I

This is the more massive of the two gates and during the time of the problem (8 μs) the temperature of the Al remains below melt where the resistivity is well-known. The magnetic pressure exceeds the yield strength of the material so the elastic wave is followed by a plastic wave and as B_θ varies by only 10.5% across the gate it moves essentially uniformly along the axis with a speed of approximately 0.075 cm/μs. Most of the energy supplied to the gate goes into plastic flow. The gate boundaries and velocities at 7.7 μs appear as in Fig. 8 which shows no evidence of breaking.

Model II

The gate here is about one-half the thickness of Model I and the notch thickness is a smaller fraction of ℓ. The velocities are shown in Fig. 9 at selected times. Initially, the behavior resembles Model I, and the gate flows plastically at the electrodes; the material at the notch moves more rapidly and by t = 3.34 μs a ring-shaped bubble has formed, but the entire gate is still in the solid phase. At t = 3.67 μs the back surface of the gate has melted, and acquires the liquid resistivity. However, the regions near the thick part of the gate are above melt. We expect the ring-shaped solid portion of the notch to develop instabilities and breakup before this point though it is not clear if this process will interrupt the current path. In fact, the bubble may expand and move downstream forming a current commutator. The calculation has been stopped at 4.86 μs, and the contours of constant rU_θ are shown in Fig. 10. At this point the bubble zoning is only marginally capable of resolving the MHD. We note that the entire bubble has melted and contains a significant amount of vapor. The back one-third of the gate has also melted and is emitting a hot, low density plasma. The resistance of the gate is approximately 3.0×10^{-2}mΩ.

2. Commutator

A variation on the moving foil commutator is the plasma gun commutator which can operate with either a gas fill or a gas puff.[19] Having a well-localized current sheath, it is particularly attractive at high current densities where the moving foil is susceptible to vaporization and spreading. If the snowplow is efficient and little gas remains behind the sheath to cause power flow problems, this option appears viable.

An example of a two-dimensional MHD calculation of a coaxial hydrogen gas fill plasma commutating current into an imploding foil (also hydrogenic) is given here. The configuration of Fig. 5 beyond the closing switch was used (i.e. gate was not included) with a = 5 cm, b = 7.5 cm, ℓ = 21 cm, and h = 1 cm. The load foil was started in an expanded state (.5 cm thick) with its outer radius located at 5 cm. The initial foil density was 2×10^{20} cm^{-3} (total mass was 10 mg) and the gas fill density was 1.5×10^{16} cm^{-3}. The initial temperature of the gas is 1 eV while the foil temperature was maintained at a low value until the plasma began to pass over it. The discharge is driven by a plate generator in a circuit similar to Fig. 1 with an initial current in the first loop of 4.8MA[20]. After switch closure the generator ΔL changes by 52 nH in 6.7 μs.

Density contours as the current sheath approaches the end of the anode are shown in Fig. 11a. Once the sheath passes over the foil, the foil is left essentially intact with some axial motion (see Fig. 11b). Fig. 11c shows the foil about to converge on axis. The $\frac{dI}{dt}$ for the imploding foil was greater than 3×10^{13} A/sec. This fast, uniform implosion makes this commutator very attractive and our investigation is continuing.

E. Zero-Dimensional Gate Model

As mentioned earlier, our MHD calculations of specific gate geometries have not shown a large increase in resistance. However, these calculations are extremely time consuming and do not allow a wide survey of parameter space to be made. In order to perform such a survey a zero-dimensional model has been used.

When the metal melts and vaporizes due to ohmic heating, the gate material will undergo a change of resistance which depends on dimensions, material properties and heating rate. The model assumes that the switch behavior can be described by its initial dimensions, its time-varying thickness, position and temperature. It is assumed that the material is homogeneous and that the magnetic field varies linearly across it. Models of specific heats and resistivites as functions of density and temperature are used. The circuit used is shown in Fig. 6. The gate (R and L_{s1}) and the commutator (L_{s2}) are accelerated according to a slug model and the closing switch is activated above a threshold voltage. The model assumes that the distance between the central and return coaxi . conductors is small compared to the radius of the central conductor to minimize two-dimensional effects. The density, ρ, is related to switch thickness, δ, by $\rho = \rho_0 \delta_0/\delta$. The evolution of the switch internal energy is determined by ohmic heating, and its expansion is described by simple expressions based on whether or not the temperature has exceeded melt. That is,

$$\frac{d\delta}{dt} = 0, \text{ if } T < T_{melt}$$

and

$$\frac{d\delta}{dt} = kT^{1/2}, \text{ if } T > T_{melt}$$

where k is a constant. The independent variables of the model are switch mass and thickness; contours of energy transferred to the load and other quantities of interest are then plotted in the (δ,M) plane. When the optimum switch and load parameters are determined, the results of our simple model computations will be verified by more complete one- and two-dimensional MHD computations. Fig. 12 shows the results of a series of calculations performed for a fixed load inductance of 5 nH. It demonstrates that there are certain combinations of (δ,M) which can lead to the transfer of over 8 MJ of energy, or, equivalently, 50 MA of current, from the generator loop to the load loop. Most of the (δ,M) combinations are not of interest because of the very large radius required for a coaxial switch. Shown in Fig. 13 is the resistance of a switch which has an equivalent coaxial inner radius of 25 cm. This switch melts and undergoes a resistance increase of nearly three orders of magnitude to 1 mΩ approximately 10 μs after the peak generator current of 82 MA. A peak dI_2/dt in excess of 10^{13} A/s is achieved and the current rises to nearly 20 MA in less than 10 μs; the maximum switch voltage is only 65 kV. Figure 13 shows that the resistance of the switch decreases rapidly from its maximum value as the melted and vaporized switch expands; a peak switch temperature of about 1 eV is reached. Our computations predict that such a switch will have moved 30 cm down the coaxial transmission line during time prior to melting.

F. High Explosive Switch Systems

The system described in the previous section using only integral switches and no internal insulators seems capable of being extrapolated to very large energies. To reach the megajoule level, systems employing fuses or high-explosive opening switches are of interest.[21] For example, recently Goforth and Caird at Los Alamos have experimented with a switch that seems capable of increasing its resistance by an order of magnitude from an initial value of $5 \times 10^{-4}\,\Omega$ at a current density of .5 MA/cm and with a voltage standoff of 30 kV/cm.[22] In a system the switch would be collinear with the generators as in the last section and have an associated inductance of 4 nH; it would be adjacent to a commutator section identical in dimensions to that in the previous section. The commutator foil has a mass of 170 mg, moves 5 cm, and reaches a speed of 9.3 cm/μs; its $\dot{L}$ does not seriously degrade the current. The aluminum load which has an initial radius of 5 cm, a length of 2 cm and a thickness of 5000Å imploded in .16 μs with a kinetic energy of 2 MJ according to zero-dimensional calculations; a voltage of only 90 kV appeared across the switch. Without the commutator, an energy of less than 300 kJ was reached because there was insufficient time for the current to rise before the load imploded.

V. SUMMARY

The Los Alamos system concept has been described with emphasis on the switching schemes. To date a large resistance opening switch has not been developed, but we find that significant amount of energy can be transferred to an imploding load at a relatively low voltage using a two-stage flux transfer system.

Acknowledgements

The authors would like to express their appreciation for information and fruitful discussions to W. Baker of the Air Force Weapons Laboratory and to C. M. Fowler, R. Caird, D. Erickson, D. Giovanelli, J. Goforth, and J. Trainor of Los Alamos.

Figure Captions

Fig. 1. Conventional MCG circuit (L_g is the time-varying MCG inductance, L_B is the ballast inductor, L_F is the imploding foil inductance, I_0 is the initial MCG current.

Fig. 2. MCG circuit with opening switch modeled as R(t). L_T is the transmission line inductance. I_S is the primary branch current at switching time.

Fig. 3. Los Alamos coaxial system

Fig. 4. Current switching section of Los Alamos system.

Fig. 5. System Equivalent Circuit. L_{S1} is the inductance of the gate switch. L_{S2} is the iductance of the commutator. Resistance of the commutator is assumed to be negligible.

Fig. 6. Kinetic Efficiency for E. = 50 MJ, ΔL = 9.2 nH, L_0 = 4.1 nH, L_1 = 13 nH. Upper Curve: m = 0.169 gm, v = cm/μs. Lower Curve: m = 1.69 gm, v = 10 cm/μs.

Fig. 7. Magnetic Gate Model.

Fig. 8. Velocity vectors of Model I at $t = 7.7$ μs. The maximum velocity of the gate is 0.74 μs. Back surface of gate was initially at $z - 2.52$ cm.

Fig. 9. Velocity vectors of Model II. (a) $t = 0.58$ μs, $v_z = 0.047$ μs; (b) $t = 3.67$ μs, maximum $v_z = 0.137$ cm/μs (in notch); $t = 4.86$ μs; maximum $v = 0.19$ cm/μs.

Fig. 10. Contours of constant rB_θ at $t = 4.86$ μs. At back surface $rB_\theta = 0.45$ m-cm and $\Delta(rB_\theta) = 0.05$ MG-cm between contours.

Fig. 11. Plasma commutator density contours. (a) $t = 2.8$ μs; (b) $t = 3.1$ μs; (c) $t = 4..1$ μs.

Fig. 12. Contours of maximum energy transferred to a 5 nH load in a circuit with gate switch characterized by (δ, M).

Fig. 13. Gatae switch resistance.

REFERENCES:

1. P. J. Turchi and W. J. Baker, J. Appl. Phys. 44, 4936 (1973).

2. R. E. Reinovsky, J. H. Degan, G. F. Kiuttu, R. A. Nuttelman, and W. L. Baker, "Megagauss Physics and Technology", P. J. Turchi et., Plenum Press, New York, 1980, p. 313

3. J. Pearlman, E. Chu, W. Clark, M. Gersten, J. Katzenstein, A. Kolb, P. Korn, R. Miller, A. Peratt, J. Rauch, R. Richardson, J. Riodan, J. Shannon, M. Wilkinson, Fourth Inter. Conf. on High-Power Electron and Ion-Beams, Palaiseau, 1981, p. 271

4. C. Gilman, G. Hahlbacka, R. Schneider, R. Stringfield, E. Buck, R. Dukart, P. Sincerny and M. Di Capua, Ref. 3, p. 287

5. J. Van Devander, G. Barr, J. Crow, S. Goldstein, D. McDanial, K. McDonald, T. Maring, B. Moore, E. Neau, G. Peterson, J. Seamon, D. Seidel, R. Spielman, B. Turman, G. Yonas, Ref. 3, p. 725.

6. S. G. Alikhanov, L. I. Rudakov, V. P. Smirnov, I. R. Yampol'skii, Sov. Tech. Phys. Lett. 5, 587 (1979).

7. R. S. Caird and P. J. Turchi, AFWL-TR-74-222, 1975.

8. T. W. Hussey, N. F. Roderick, and D. A. Kloc, J. Appl. Phys. 51, 1452 (1980).

9. J. H. Degnan et al., "Tests of a Helical Explosive Generator to Ten Megajoules", (these proceedings).

10. R. S. Caird et al., "Design of a 20 MJ Coaxial Generator", (these proceedings.

11. D. J. Steinberg and J. W. Shearer, Ref. 2, p. 361.

12. P. J. Turchi, G. Bird, C. Boyer, D. Conte, J. Davis, L. De Raad, G. Fisher,L. Johnson, A Latter, S. Seiler, D. Thomas, W. Tsai and T. Wilcox, Third IEEE Pulsed Power Conference, Albuquerque, 1981, p. 455.

13. D. R. Kania, R. J. Trainer, E. L. Zimmerman, L. A. Jones, L. Veeser, J. D. Seagrave, Fourth IEEE Pulsed Power Conference, Albuquerque, 1983. n

14. S. I. Braginskii, JETP 6, 358 (1958).

15. J. Chase, private communication.

16. M. Williams, UCRL-Rev. 1, 1969.

17. D. J. Steinberg, S. G. Cochran, and M. W. Guinan, J. Appl. Phys. 51, 1498 (1980).

18. J. LeBlanc, private communication.

19. J. Brownell, I. Lindemuth, B. Freeman, Bull APS. 27, 1032 (1982).

20. R. S. Caird et al., "A Circuit Model for the Explosive-Driven Plate Generator," (these proceedings).

21. A. I. Pavlovskii, V. A. Vasyukov, A. S. Russkov, Sov. Tech. Phys. Lett. 3, 320 (1977).

22. J. H. Goforth and R. S. Caird, Fourth IEEE Pulsed Power Conference, Albuquerque, 1983.

TABLE I

Model	ℓ (cm)	a (cm)	b (cm)	c (cm)	mass (g)
I	0.22	0.072	0.18	0.85	107.5
II	0.126	0.074	0.138	0.72	59.1