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AUTHOR(S): R. S. Caird, C. M. Fowler, D. J. Erickson, B. L. Freeman and W. B. Garn

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A SURVEY OF RECENT WORK ON EXPLOSIVE-DRIVEN MAGNETIC FLUX COMPRESSION GENERATORS*

R. S. Caird, C. M. Fowler, D. J. Erickson, B. L. Freeman
and W. B. Garn[†]

Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87545 USA

ABSTRACT

There are five widely-used classes of explosive-driven flux compression generators. They are the spiral, coaxial, strip, plate and cylindrical implosion systems. The configurations will be described and the characteristics of the various types compared. There are a number of techniques for sharpening or impedance-matching the output pulse of the generators. The use of switching, fuses and transformers will be discussed. Some of the areas of application of the generators will be outlined briefly. Much of the recent work at Los Alamos has been directed toward the development of the plate generator. This type consists essentially of a transmission line with explosive slabs on the flat surfaces. These plates may be parallel or at an angle with respect to each other. A plane detonation front in the explosive allows a large area of conductor to be driven simultaneously. As a result, the power and current outputs are very high --- many megamperes at the terawatt level. This generator is particularly well suited to driving low impedance plasma devices. The results of our plate generator tests will be discussed.

INTRODUCTION

An explosive-driven magnetic flux compression generator is a

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*Work supported by the United States Department of Energy.

[†]Consultant.

device for converting the chemical energy of explosives into electrical energy. Since the energy content of explosives is about 5 MJ/kg, it is possible to construct very light weight, compact power supplies with high energy and power outputs. The pressure of the detonating explosive accelerates a portion of the conductor forming the boundary of the generator to velocities in the range 0.5-5 km/s. The geometry is arranged so that the motion of the conductor decreases the inductance of the generator. If there is an initial magnetic flux linking the generator and if the associated circuit has a sufficiently low impedance, the current and magnetic field can build up to the point where a substantial part of the kinetic energy in the conductors is extracted in the form of electrical power.

The first part of this paper takes up the general properties of explosive-driven generators --- the way they behave as circuit elements, the different types and their characteristics, the adaptation to various load requirements and the operational peculiarities. The last section deals with the areas in which generators have been and can be used. As these topics are discussed, we shall cite some of the recent work in the field. The first four references[1-4] cover the fundamentals of explosive-driven generators and most of the developments up to 1970.

FUNDAMENTAL FRAMEWORK

The basic behavior of a generator can be characterized by considering the simple one-loop circuit shown in Fig. 1. The generator is represented by a variable inductance L_G driving a resistance R(t) and a fixed inductive load λ. Letting L be the total circuit inductance, we can write the voltage equation for the loop as

$$\frac{d}{dt}(LI) + RI = 0. \tag{1}$$

An equivalent form is

$$\dot{I} = -I(R + \dot{L}_G)/L, \tag{2}$$

where the dot notation is used to denote the time derivative. The initial condition is $I(0) = I_0$. Integration of Eq. 2 yields

$$I(t) = I_0\,[L(0)/L(t)]\,\exp\left\{-\int_0^t [R(t')/L(t')]dt\right\}. \tag{3}$$

The energy delivered to the inductance λ is

$$E_\lambda(t) = E_0[L(0)/L(t)]\,[\lambda/L(t)]\,\exp\left\{-2\int_0^t [R(t')/L(t')]dt'\right\}, \tag{4}$$

where $E_0 = \frac{1}{2}L(0)I_0^2$. The power input to λ is

$$P_\lambda(t) = -2E_\lambda(R + \dot{L}_G)/L(t). \qquad (5)$$

Since the generator inductance is decreasing, $\dot{L}_G$ is negative.

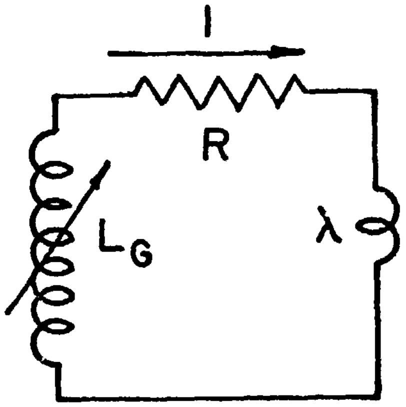

Fig. 1. Elementary generator circuit. L_G represents the generator.

Several important conclusions can be drawn from these equations. First, referring to Eq. 3 and viewing R as the load, we see that an explosive-driven generator is not well suited to driving a large resistance. The negative exponential tends to suppress the current multiplication, $I(t)/I_0$, upon which the generator depends for extracting energy. Second, we may view R as representative of the losses within the generator itself, in which case the exponential equals the ratio of the flux at time t to the initial flux. Flux losses can arise from field diffusion into the conductors and trapping at points of sliding contact. The exponential enters the energy equation squared, and thus the flux loss strongly influences the energy multiplication, $E_\lambda(t)/E_0$. Finally, two quantities are needed to describe a generator as a circuit element: the initial inductance, which is readily calculated or measured, and L_G (t, I). Considering Eq. 2, we may include the loss term R in L_G and obtain a good description of the generator. The current dependence sometimes is necessary to allow for flux diffusion and magnetic pressure effects.

We are in a position to define some figures of merit for the explosive-driven generator. The first is energy multiplication, EFM = $E(t)/E_0$. We see from Eq. 4 that this quantity is determined by the generator initial inductance, the load inductance and the losses. In addition, for many applications, it is of great importance to know how quickly this energy is delivered to the load. Therefore, we shall also define a power figure of merit PFM, where

$$PFM = P_\lambda/E_\lambda = -2(\dot{L}_G + R)/L(t). \quad (6)$$

We see that this quantity, having units of reciprocal time, is determined primarily by $\dot{L}_G$ and the circuit inductance. When multiplied by the energy, the PFM gives the power input to the load inductance. To be meaningful, both the EFM and PFM should be evaluated near the end of the generator run.

Some source of initial magnetic flux is needed for the generator. The usual injection technique is to establish a current in the generator circuit using a capacitor discharge. When the detonation front reaches the input conductors of the generator, the circuit is crowbarred and the flux trapped. However, it is quite feasible to use other methods, for example, an external coil energized with a capacitor bank or a DC current or even a system of permanent magnets. If the weight of the total power supply is a consideration, it is important which technique is chosen. In a series of experiments conducted at Los Alamos, the effects of different injection techniques on the generator output were compared.

The tests in question were performed in the course of designing a power supply for a rocket-borne plasma experiment.[5] It was required to deliver several megajoules to the plasma gun within a weight limitation of 250 kg. Since it is possible to store a higher energy density in a magnetic field than in a capacitor dielectric, a superconducting coil was employed to provide the initial flux for a spiral generator. A scaled-down version of the final generator and coil system was built and tested. The coil was wrapped as closely around the generator as the cryogenic system would permit. Rogers[6] has described the Nb-Ti superconducting coil used in the experiments. However, we also tested three other flux injection schemes using the same generator. Referring to Fig. 2, curve A resulted from an injection coil wound on a phenolic form and energized by a capacitor bank. For curve B, the external coil was wound on metal components simulating the cryostat and the initial current risetime was twice as long as that for curve A. Curve C is the result of a test with the superconducting coil. For the dashed curve, the generator was fed directly with the capacitor bank. All the curves have been normalized to the same initial flux. These results suggest that generator performance improves as the risetime for flux injection increases.

A comment should be made concerning the width of the output conductors. To extract a significant fraction of the kinetic energy from the moving conductors, it is necessary to have them do work against as high a magnetic pressure as possible. This requirement implies high current densities with consequent heating and deformation of the conductors. A practical limit for surface current densities in the generator output is in the range 100-200 MA/m, depending on the rise time. The width of the conductors often determines the maximum current and, for a given load, the maximum energy that a generator can deliver. The maximum current is another important figure of merit.

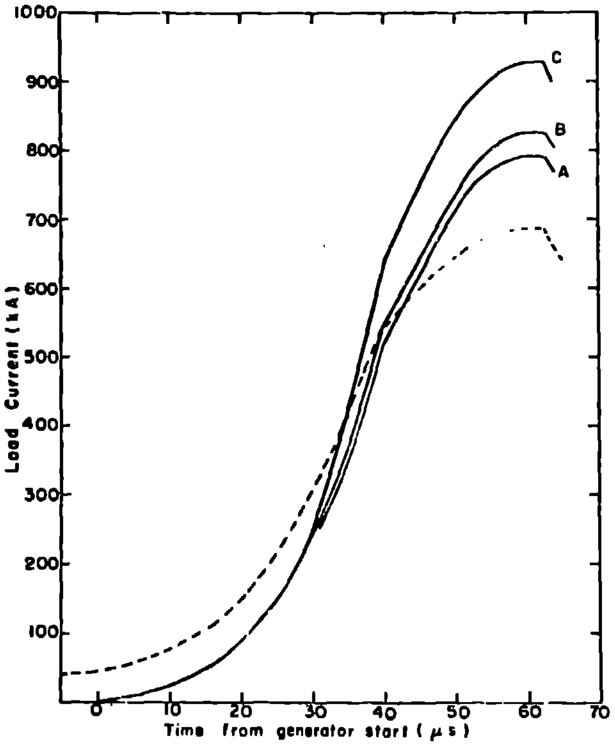

Fig. 2. Currents produced with four different flux injection techniques using the same generator. The curves are normalized to the same initial flux.

A final point concerns the use of more than one generator in a circuit. Frequently the initial energy source is not large enough to provide the required current to the generator that drives the load. In this case, a booster generator can be used in series with the final generator to increase the total current and energy multiplication. Initiation of the second generator is timed to occur when the booster reaches maximum output. If a very high output current is desired, several generators may be attached to the load in parallel and timed to run simultaneously. Alternatively, higher voltages may be obtained by running several generators in series, effectively adding the L_G's of the ensemble. The flexibility offered by employing these techniques greatly enhances the usefulness of explosive-driven generators.

GENERATOR TYPES AND CHARACTERISTICS

It is convenient to classify explosive-driven generators into five types --- spiral, coaxial, strip, plate and cylindrical implosion generators. This classification scheme is by no means exhaustive, but it does include the varieties that have seen the most use up to the present. Considerations of cost, high-voltage insulation and availability of initiation systems usually eliminate more exotic geometries.

Spiral Generators

The spiral or helical generator, illustrated in Fig. 3, has the advantage of a large initial inductance packaged in a small volume. The hollow armature is filled with explosive, which is detonated at the input end. The armature, usually made of aluminum or copper, expands in a cone which moves at detonation velocity toward the output. The input is crowbarred first. The contact point between the armature and the generator coil then moves in a helical path, sweeping the flux ahead. The great length of the path traced out by the contact gives rise to considerable flux loss. However, this loss is offset by the fact that the initial inductance is roughly proportional to the square of the number of turns and, therefore, the length. The turns near the input usually have a small cross section and are close together since they do not carry much current during the early part of the generator burn. At the output end, the turns are paralleled and have a larger cross section in order to carry higher output currents.

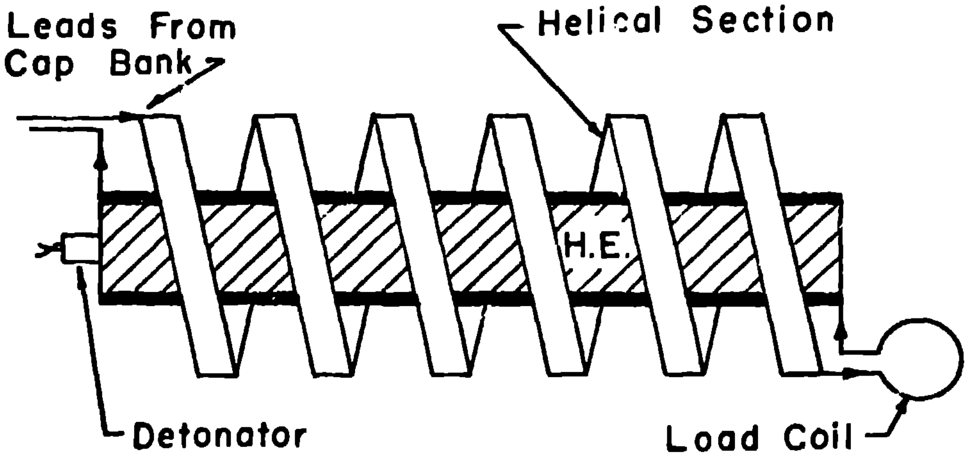

Fig. 3. Spiral or helical generator.

The spiral generator has by far the best EFM of the various types for a given volume owing to the large initial inductance. However, $|L_G|$ decreases drastically as the armature expansion approaches the output and falls to less then 3 mΩ during the last few microseconds of run. As a result, the PFM is less than 2 x 10^5 $\sec^{-1}$ for a typical 100-nH load. The spiral generator is often used as a booster stage for generators having a larger PFM. Antoni et al.[7] describe a spiral generator which was used with a fuse to drive a plasma focus. Some interesting preliminary work is reported by Cnare et al.[8] in which the generator coils are not destroyed.

Coaxial Generator

This generator is basically a coaxial transmission line in which the inductance is changed either by imploding the outer conductor or exploding the inner conductor. Figure 4 shows the first of these geometries. A ring of detonators at the input end initiates the jacket of explosive. The current is parallel to the generator axis, and the flux lines encircle the inner conductor. The reason for usually imploding the outer conductor rather than exploding the inner conductor is that the initial inductance may be increased somewhat by making the center conductor smaller. However, the final burn stage of a spiral generator is often very similar to that of a coaxial generator with an exploding armature. The core tapers up to a larger diameter at the output end to increase the current-carrying capacity. The losses are less than those of the helical generator, but its relatively low initial inductance compared to its volume makes it suitable only for low inductance loads requiring very large currents. The large amount of explosive in the jacket makes the outside-in geometry quite inefficient compared to other generator types. The $|L_G|$ attainable with this generator is typically about 1 mΩ near burnout, corresponding to a PFM of about 10^6 $\sec^{-1}$ for a load of 2 nH. Because of the cylindrical shape, the current-carrying capacity is high (about 100 MA for a 30-cm conductor diameter, for example). The low initial inductance is usually offset by employing a booster generator.

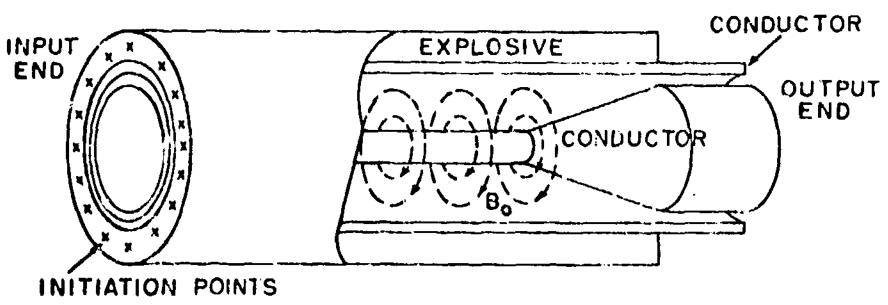

Fig. 4. Coaxial generator with imploding outer conductor..

Strip Generator

The strip or planar generator (also referred to as a plane or bellows generator) is depicted in Fig. 5. Again, the explosive train is initiated at the input end. The total burn time is similar to that of the spiral and coaxial generators for the same length. This generator is essentially a strip transmission line in which the inductance is varied by decreasing the strip separation. To increase the initial inductance without sacrificing current-carrying capacity, the conductors may be narrow at the input end and wider at the output. The initial inductance is usually greater than that of the coaxial generator owing to the narrower effective width. The current capacity is correspondingly less. The $|\dot{L}_G|$ is typically about 2 mΩ during the last microsecond of run. The great advantage of the strip generator is that it is much less expensive than the other types. The driver plates can be made from stock sheet metal using a shear and a brake. The explosive is often commercially available sheet explosive that needs no machining. As a result, the planar generator is widely used. One interesting development is the minigenerator reported by Fowler et al.[9] Fields of 110 T have been produced in a 10-mm-diameter load coil using less than 90 g of explosive. This technique makes it possible to perform high field experiments in an environment very close to that of the laboratory.

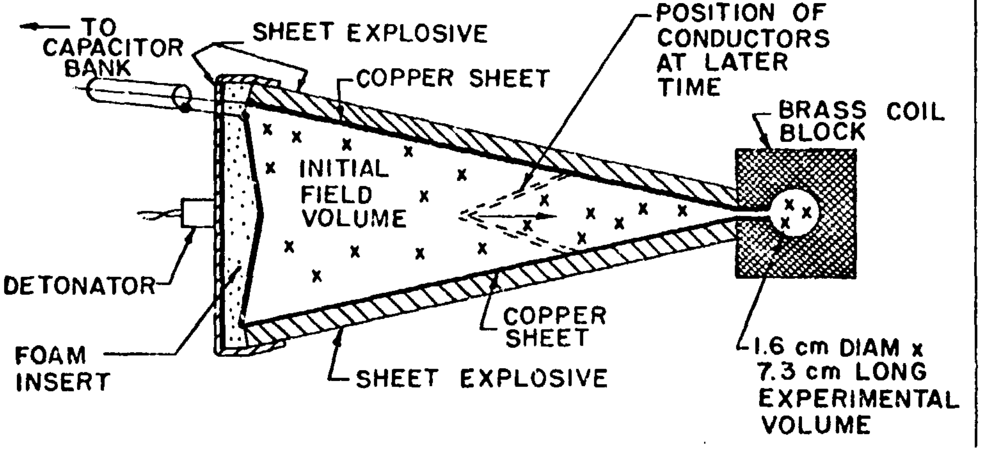

Fig. 5. Strip or planar generator used for high field experiments.

Plate Generator

The power output of any of the preceding generator types would be greatly improved if the entire length of the armature could be moved simultaneously. The inductance would decrease more rapidly in this case. Such an improvement has been observed for coaxial generators.[10] The plate generator is such a modification of a strip or planar generator. The crucial difference is that a plane initiation system is used to drive the plates simultaneously over their entire areas. This type of generator is illustrated in Fig. 6. The initial inductance can be about the same as that of the strip generator, but $|\dot{L}_G|$ is much greater. Based on our recent efforts[11] to develop and employ this type of generator, we provide the following comments.

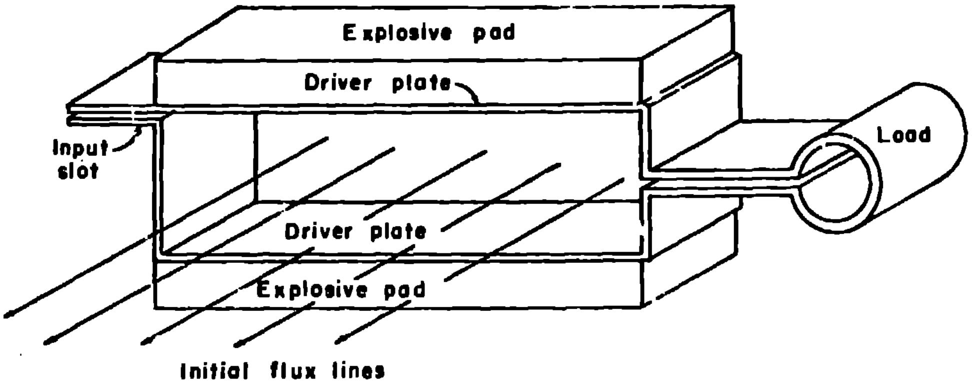

Fig. 6: Plate generator with coil load. The explosive pads are initiated with a plane-wave system.

It is possible to change the time variation of the plate generator inductance in a simple way by varying the initial plate separation at the input end. The variants are indicated by the outline drawings in Fig. 7. The corresponding changes in $\dot{L}_G$ are shown in Fig. 8. These results were obtained using a generator model that takes into account most of the physical processes occurring in the generator volume. The PFM of the rectangular form is about 3×10^6 sec^{-1} with a 30-nH load. The comparison between theory and experiment is illustrated in Fig. 9. The driver plates are 51 cm long, 15 cm wide and have a separation of 12.7 cm at the output end. The voltage across a 30-nH load for 1 MA of initial current is shown in Fig. 10. This wide range of voltage available near the end of the generator run has proved to be valuable in our plasma focus experiments.[5] It is worth noting that if the rectangular version is driven to maximum output (∿ 12 MA), the predicted energy in the load is 2.3 MJ and the predicted peak power is 4 TW.

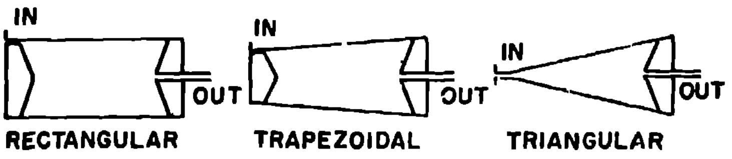

Fig. 7. Variations of the plate generator arising from varying the input plate separation.

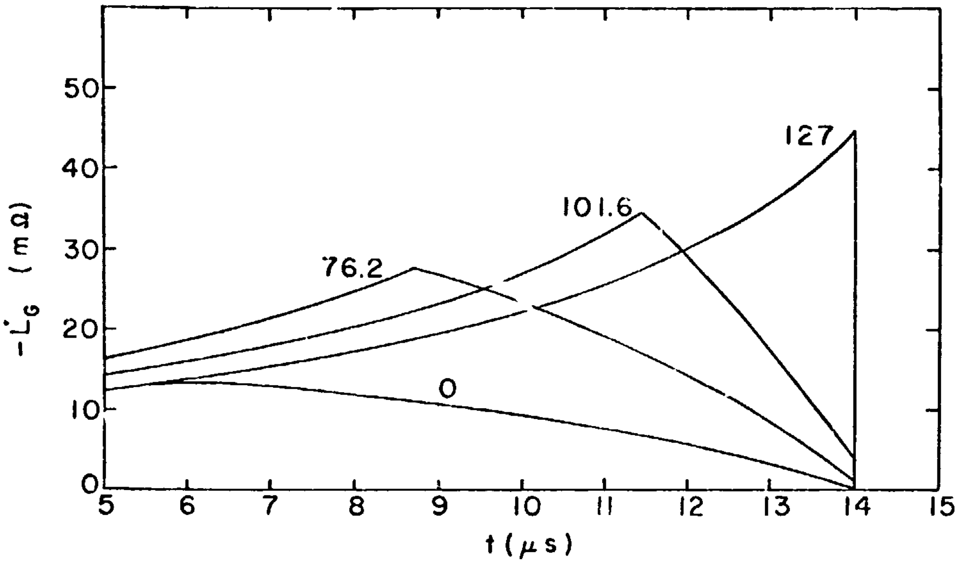

Fig. 8. Time variation of $-\dot{L}_G$ for differing input plate separations. The curves are labelled according to the input plate separation in millimeters.

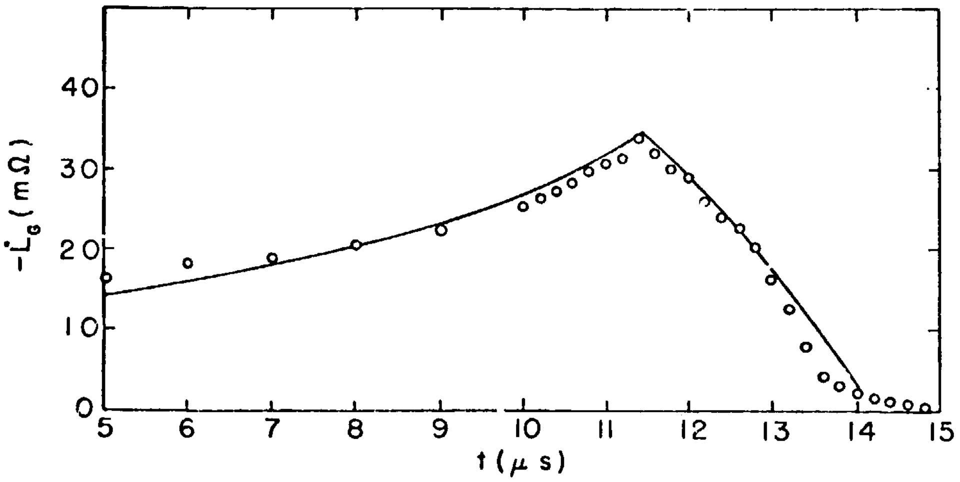

Fig. 9. A comparison of the predicted generator behavior (solid line) with experimental results (circles) for a 101.6-mm input separation.

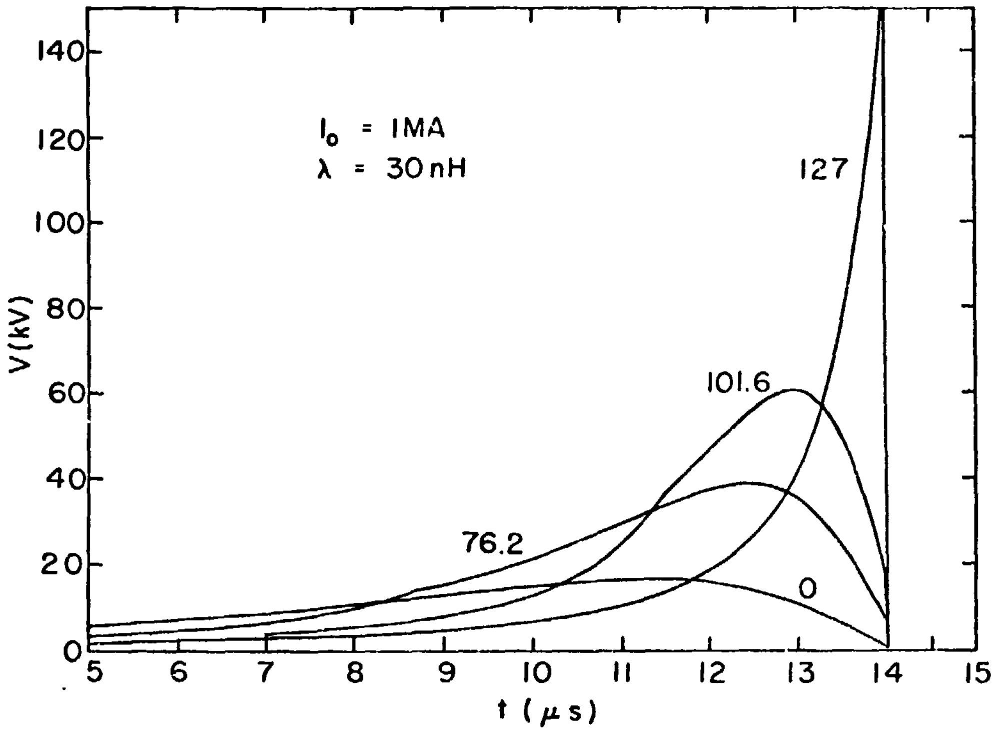

Fig. 10. Predicted time variation of the load voltage with curves labelled according to input separation (mm). The curve labelled 127 reaches 167 kV at 14 μs.

Cylindrical Implosion Generator

The last type to be described is the cylindrical implosion generator, shown in Fig. 11. An initial magnetic field is induced within a hollow metal cylinder called the liner. A ring of explosive around the liner is initiated on the periphery, driving the liner inward toward the axis. There are two different modes of initiation. In one, the explosive is touched off in a ring at one end of the cylinder. As the detonation front travels along the length of the explosive, the field compression follows behind with maximum compression occurring at different times at different points along the axis. The second mode requires simultaneous initiation over the surface of the explosive and provides almost simultaneous compression over most of the liner length. The cylindrical implosion generator occupies an anomalous position with respect to the others. Because all the conductor around the generator volume is subject to the pressure of the detonating explosives, it is possible to reach surface current densities in excess of 1500 MA/m. However, it is extremely difficult to transfer the energy to a load outside the liner volume. One can place a small coil on the axis, but the voltages induced are very high and lead to insulation problems that have not been solved. This generator has been used to produce high fields, which are used *in situ*. Hawke et al.[12] have developed a cylindrical implosion system for use in the isentropic compression of hydrogen to pressures above 200 GPa.

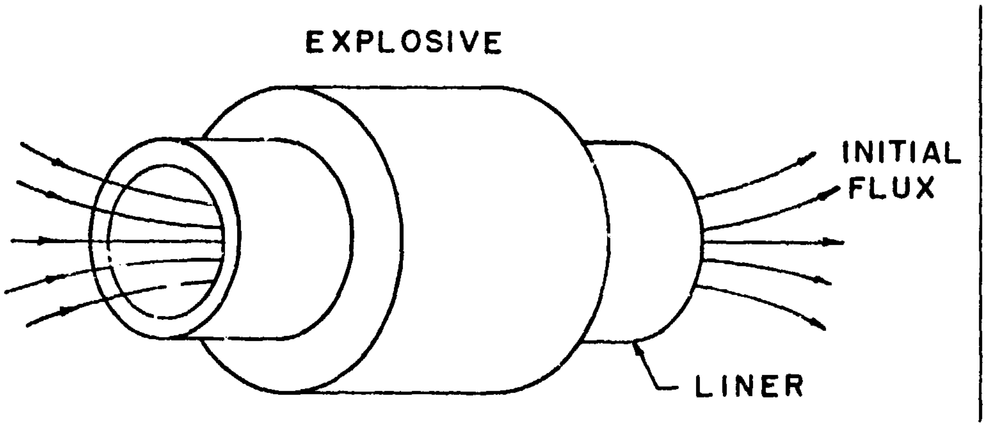

Fig. 11. Cylindrical implosion generator. The explosive is initiated on the outside surface.

PULSE SHARPENING AND IMPEDANCE MATCHING

It is often necessary to alter the output of an explosive-driven generator for effective use. Here, we shall describe three commonly used techniques for applying the generator output to a load. The first technique is the use of a ballast or shunt load and a switch. Figure 12 shows a schematic of the circuit. Compared to the effective rise time of most generators, the time required to establish the initial current and burn the explosive is very long. Many loads cannot tolerate a current flowing through the circuit at a low level for times ranging from 45 to 400 µs. Most plasma devices fall into this category. A simple solution is to provide an inductance, the ballast load, through which the current can flow until the generator is in the fast region of rise. The switch then closes, connecting the load in parallel with the ballast inductor across the generator output. Because there is always a limitation on the current available, some sacrifice is entailed in leaving the ballast in the circuit. In many applications, however, one can choose a shunt load with an inductance low enough not to impair generator multiplication during the early part of the run but high enough to insure that the load receives the larger share of the current after switching. The switch is usually a detonator-actuated dielectric switch. There are also ways, however, to arrange for the moving conductors to effect the closure. Another option is to use a voltage breakdown switch.

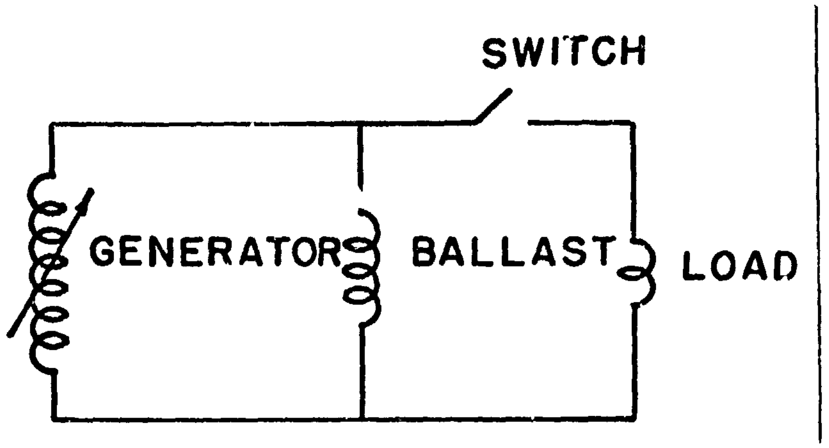

Fig. 12. Equivalent circuit using ballast load and switch.

The basic fuse circuit is shown in Fig. 13. Energy is deposited in the fuse resistance, raising the temperature until the conductor vaporizes. Then the resistance rises very rapidly and shuts off the current passing through the fuse leg of the circuit. There are two different ways to use a fuse. In the first, the fuse replaces the ballast load of Fig. 12. A low inductance package permits good multiplication during the earlier portion of the generator run. Timing is arranged so that as the load is switched in, the fuse vaporizes, effectively removing the ballast from the circuit and preventing further drain upon the generator output. It appears feasible to achieve this behavior without losing much energy in vaporizing the conductor and without generating excessively high voltages. The current rise time in the load is the same as that of the generator without the fuse.

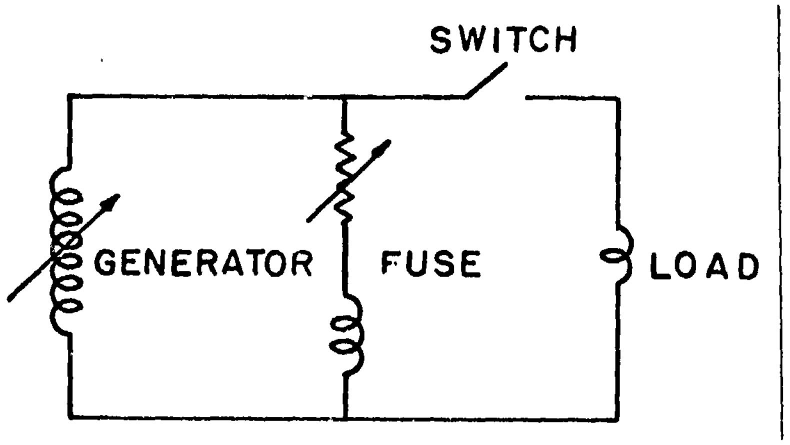

Fig. 13. Equivalent circuit for fuse technique.

The second mode of operation uses the fuse circuit to sharpen the current rise time relative to that of the generator itself. Most of the energy is first stored in the fuse inductance. Near the end of the generator run, the fuse is designed to vaporize and transfer to the load through the switch very quickly. There are formidable problems associated with the high voltages produced because the vaporized fuse material must stand off these voltages. Despite the problems, several groups have used the fuse to shorten the rise time of spiral generators. Crawford and Damerow[13] have achieved a dI/dt of 4 x 10^{12} A/s and applied the technique to both plasma focus devices and theta pinch coils. More recently, Azarkevich et al.[14] described experiments in which a generator, through a transformer and fuse, powered a 0.4-Ω load. The current rise time was 4 x 10^{11} A/s at 140 kA. Antoni et al.[7] achieved 3 x 10^{11} A/s at 2 MA.

Transformer coupling for most applications is employed with high impedance loads that require a high-voltage, low-current source rather than the low-voltage, high-current output typical of explosive-driven generators. The circuit of Fig. 14 shows a resistor as typical of such a load. The principal difficulties arise in attempting to satisfy the mutually incompatible requirements of close coupling between the primary and secondary of the pulse transformer and good voltage standoff. In the transformer-fuse experiments of Azarkevich et al.,[14] voltages of 100 kV were achieved. Villere and Luessen[15] obtained voltages of nearly 200 kV with a 120-Ω load using spiral generators. Voitenko et al.[16] and Divnov et al.[17] have used pulse transformers to match explosive-driven generators to inductive loads, although the voltages achieved are not stated. In work yet to be published, we have produced 1.1 MV across a 25-Ω load using a rectangular plate generator. The pulse transformer used foil windings and dielectric grading techniques.

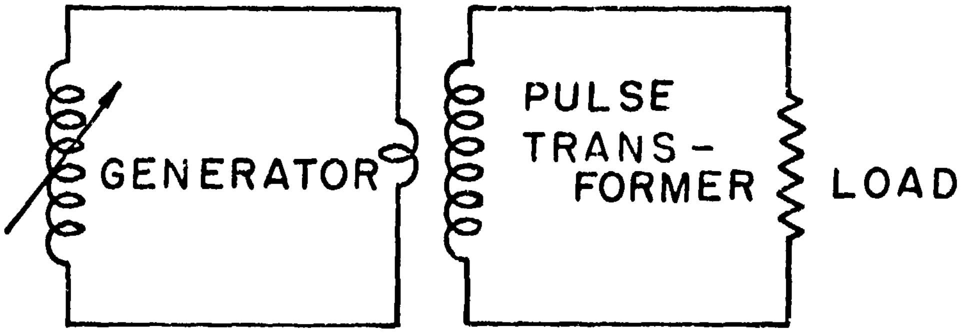

Fig. 14. Equivalent circuit for pulse transformer impedance matching.

APPLICATIONS

Explosive-driven generators are very powerful and portable power supplies. It is possible to obtain megajoules and terawatts from a device that a person can lift. Bichenkov et al.[18] speak of firing explosive-driven generators in laboratory experiments. Voitenko et al.[19] describe the confinement chamber used for such experiments. In principle a generator can be used in any application that requires high pulsed power and energy. In this section, we shall take up some of the areas particularly suited to these power sources.

The generation of high magnetic fields has been an important application of explosive-driven generators. Used directly, fields exceeding 100 T have been employed to investigate the spin-flop to paramagnetic transition in MnF_2,[20] the exciton spectrum in GaSe,[21] and the Faraday effect in NiO,[22] $Gd(PO_3)_3$,[23] iron garnets[24] and some of the Zn(VI) compounds.[25] Intense magnetic fields can also be used to transmit pressure to a sample by surrounding it with a conductor (500 T is equivalent to 100 GPa). Pavlovskii et al.[26] have used generators to investigate the compression of quartz up to 150 GPa. Hawke et al.[27] have measured the compression and conductivity of hydrogen and neon up to 300 GPa. Many of the possibilities utilizing these techniques have been recently discussed elsewhere.[28]

High power explosive-driven generators are particularly well suited to driving plasma devices. Many such experiments have been reported during the past decade. The companion survey paper of Fowler et al.[5] reviews these types of applications. Another possibility is the use of generators to power particle beam accelerators. An imaginative scheme has been outlined by Winterberg.[29] A cylindrical implosion system was proposed as the 50-MV power source. The practical difficulties of such a system have been mentioned. Pavlovskii et al.[30] have built and operated an aircore betatron with a generator as the power source. An electron energy of 100 MeV was obtained. One megajoule was transferred to the betatron coils. Low impedance plasma diodes offer further opportunities. It should be feasible to replace the Marx capacitor bank and perhaps part of the water line with an explosive-driven generator to produce a very high energy e-beam machine.

The variety and capability of explosive-driven generators make possible the testing of concepts that require very high powers and energies to establish proof of principle before making huge capital investments. There are several thermonuclear fusion schemes that fall into this category, for example. It also may be time to establish a high field facility using explosive-driven generators for a systematic and organized attack on the physics of materials at high fields and pressures. There is a great wealth of possibilities that have yet to be touched.

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