Dec. 16, 1969 R. L. CONGER ET AL 3,484,627

EXPLOSIVE PULSE GENERATOR

Filed March 6, 1968

FIG. 1

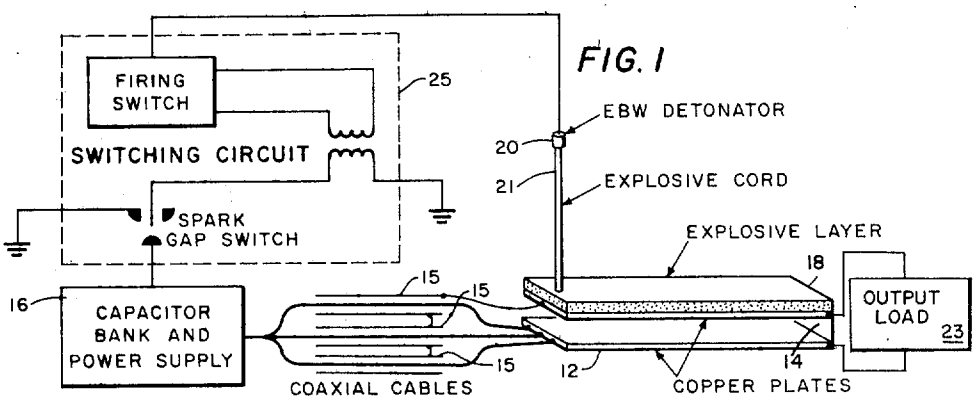
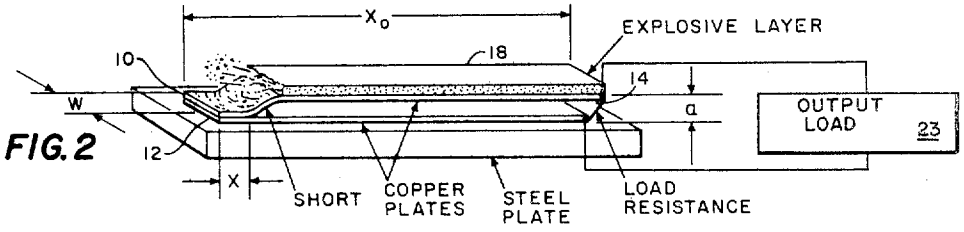


FIG. 2



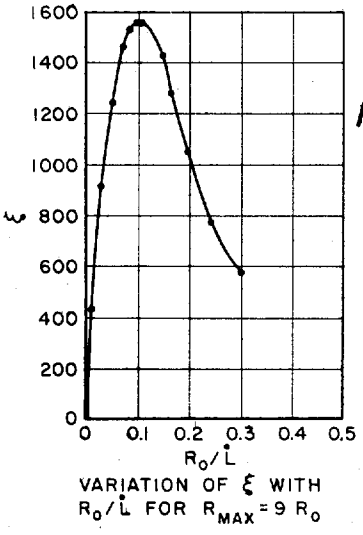


FIG. 4

VARIATION OF ξ WITH $R_o/\dot{L}$ FOR $R_{MAX} = 9\ R_o$

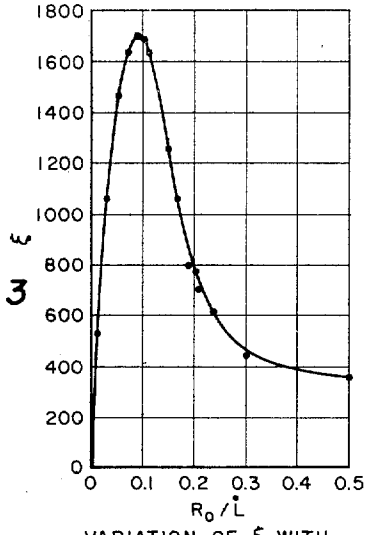


FIG. 3

VARIATION OF ξ WITH $R_o/\dot{L}$ FOR $R_{MAX} = 12\ R_o$

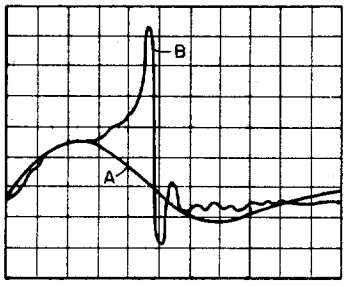


FIG. 5

FIELD COMPRESSOR OUTPUTS

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EXPLOSIVE PULSE GENERATOR

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U.S. Cl. 310—10 7 Claims

ABSTRACT OF THE DISCLOSURE

An explosive magnetic flux compressor for producing high current pulses with optimum flux build up and maximum current delivered to the output load. A variable load resistance which initially shorts out the output load, operates to switch current generated in the compressor to the output load as resistance is increased in the variable load resistance from heating due to high current generated in the compressor.

The invention herein described may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties therein or therefor.

This invention relates to the production of high power pulses by magnetic field compression and more particularly to high efficiency conversion of chemical energy to electrical energy by means of explosive magnetic flux compression.

A transient field of the order of 100 kg., lasting for a few hundred microseconds, can be produced by discharging a capacitor bank into a strongly constructed solenoid of a few turns. Higher fields cannot be obtained because the forces produced by the magnetic field destroy the solenoid. However, fields of over a million gauss can be produced by using high explosives (R. S. Caird, W. B. Garn, D. B. Thomson, and C. M. Fowler, J. Appl. Phys., vol. 35, p. 781 (1964)) to implode a one-turn coil in the form of a cylinder. If the implosion takes place in a time small compared to the decay time of current in the cylinder, the total flux will be conserved and the magnetic field will be inversely proportional to the decreasing volume of the cylinder. Cold rolled copper and stainless steel have a high enough conductivity for field compressors of this type. Although the cylinders are usually circular, they can be of other shapes, such as the geometry of the flat field compressor described herein.

Since the energy in the magnetic field is given by the integral

$$\epsilon = \tfrac{1}{2}\int \mu H^2 dV$$

(J. A. Stratton, Electromagnetic Theory, International Series in Pure and Applied Physics. New York: McGraw-Hill, 1941, p. 124) and the field is roughly inversely proportional to the volume, the energy in the field compressor is also inversely proportional to the volume and therefore is increased in the implosion. This increase comes from the chemical energy of the explosive. If the initial field before the implosion is sufficiently high, 10 percent or more of the energy in the explosive can be transferred to the magnetic field energy. At the limit of the implosion, the magnetic pressure exceeds the pressure produced by the explosive and the field starts to expand again. Since the current in the compressor is proportional to the magnetic field, this current is also inversely proportional to the volume of the compressor.

Although the magnetic field compressor converts the chemical energy of the explosive to electrical energy with high efficiency, getting this energy out can be difficult. The conductance of the field compressor plus any constant load applied during the compression must be sufficiently

high so that the decay time of the magnetic field is much longer than the time of the implosion. More efficient conversion of the chemical energy is obtained by the present invention where if the field is compressed with little or no energy removed, and then, after the field is compressed, the current is switched to an external output load by placing in the circuit of the field compressor a strip of material which has a high conductivity when cold but has a small enough mass so that it is heated to a high temperature by the high current in the compressor and strip. Thus, as the strip heats up, the resistance of the strip increases, switching the current to the load.

In the explosive magnetic flux compressor of the present invention the external output load is shorted out with an optimal temperature sensitive variable load resistance which varies with time as a function of current induced heating permitting greater energy transfer to a load.

Other objects and many of the attendant advantages of this invention will become readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with th accompanying drawings wherein:

FIG. 1 is a block diagram of a magnetic field compressor system of the present invention.

An explosive layer **18** attached to the top of plate **10** has a detonator **20** and explosive cord **21** for initiating the explosive layer from one end. Switching means **25**, comprising a firing switch and spark-gap switch for example, is connected to fire detonator **20** and discharge capacitor bank **16** into the conducting loop of the compressor.

THEORY OF MAGNETIC FIELD COMPRESSION

Magnetic field compression calculations can be based on the integral form of Maxwell's equation:

$$\int \nabla \times E \cdot da = -\frac{d}{dt}\int B \cdot da \times 10^{-8} \qquad (1)$$

where E is the electric field, B is the magnetic field, t is the time, and cgs units are used.

From a vector identity and Ohm's law,

$$\int \nabla \times E \cdot da = \oint E \cdot dl = iR \qquad (2)$$

where R is the resistance of a cylinder in which the field is being compressed and i is the current.

A flat magnetic field compressor constructed as shown in FIG. 1 is illustrated in FIG. 2 with dimensions for deriving the equations that follow. Detonation of the left end of explosive layer **18** would cause a short between plates **10** and **12** to advance to the right at the detonation velocity v. For this geometry Equations 1 and 2 give the differential equation

$$-a(X_o - X)\frac{dB}{dt} + aB\frac{dX}{dt} = iR \times 10^8 \qquad (3)$$

FIG. 2 shows an embodiment of the magnetic field compressor as implosion commences.

FIG. 3 shows magnetic field compression energy transferred to a tungsten load as a function of initial resistance R_o and inductance change $\dot{L}$.

FIG. 4 shows magnetic field compression energy transferred to a tantalum load as a function of initial resistance R_o and inductance change $\dot{L}$.

FIG. 5 shows magnetic field compressor outputs in comparison tests with and without use of explosive.

A flat magnetic field compressor can be constructed as shown in FIG. 1, for example, from a pair of spaced apart copper plates **10** and **12** connected together at one end by a load resistance **14** to make a one-turn solenoid coil in the form of a flat hollow cylinder or conducting loop.

This one-turn solenoid coil which forms the walls of the field compressor is connected via coaxial cables **15**, for example, to a capacitor bank **16** which when discharged produces an initial magnetic field in the field compressor. When an axial magnetic field is established in the hollow space within the field compressor, the magnetic lines of force form loops tied around copper plates **10** and **12** which form the walls of the field compressor. The magnetic field lines cannot escape without cutting through the conducting walls, and thus produce currents and magnetic fields which oppose the trapped magnetic field.

If edge corrections are neglected

$$B=2\pi i/5w \tag{4}$$

and thus

$$\frac{5wRdt\times10^8}{2\pi a(X_o-X)}=\frac{dX}{X_o-X}-\frac{dB}{B} \tag{5}$$

The advancing shock wave from the explosive drives the conductors of FIG. 1 together at a velocity v, so that $X=vt$. Substitution of this value for X in Equation 5, followed by integration, gives

$$B=B_o\left(1-\frac{X}{X_o}\right)^{\beta-1} \tag{6}$$

where

$$\beta=\frac{5wR\times10^8}{2\pi av} \tag{7}$$

If $R=o$, then B is inversely proportional to $1-X/X_o$, and the field is inversely proportional to the volume between the plates; but for R finite some of the magnetic field leaks through the conductor. If $\beta\geq1$, no field compression takes place.

Since B is proportional to i, Equation 6 can be written in terms of current to give

$$i=i_o\left(1-\frac{X}{X_o}\right)^{\beta-1} \tag{8}$$

For $\beta\gg1$ and $X\ll X_o$, the logarithm of Equation 8 gives

$$ln\frac{i}{i_o}\cong\beta ln\left(1-\frac{X}{X_o}\right)\cong-\frac{\beta X}{X_o}=-\frac{\beta vt}{X_o} \tag{9}$$

or

$$i=i_oe^{-\beta vt/X_o} \tag{10}$$

The inductance of the field compressor shown in FIG. 2 is given by

$$L=\frac{2\pi a(X_o-X)\times10^{-8}}{5w} \tag{11}$$

if edge connections are neglected. From Equations 7 and 11

$$\beta=RX_o/L_ov \tag{12}$$

where L_o is the value of L when $X=0$. For $X\ll X_o$ and by the use of Equation 12, Equation 10 can be written as

$$i\cong i_oe^{-Rt/L} \tag{13}$$

which is the usual equation for the decay of current in an inductance. Field compresion must take place in a time that is small compared to the L/R time constant of the field compressor.

When β is expressed in terms of Equation 12, Equation 6 can be applied to geometrics other than the one shown in FIGS. 1 and 2. In particular, it can be applied to a helical coil with a metal tube mounted axially inside the coil. In a field compressor of this form, the field is compressed between the coil and the tube as the tube is expanded explosively starting at one end. Since this type of field compressor can have a much higher inductance than the one shown in FIGS. 1 and 2, the impedance can also be much higher.

When the resistance R of the field compressor is constant, the energy transferred to it is given by the integral

$$\epsilon=\int_0^t i^2Rd\tau=i_o^2R\int_0^t\left(1\frac{v\tau}{X_o}\right)^{2\beta-2}d\tau \tag{14}$$

This integral can be maximized by differentiating with respect to R and setting the result equal to 0. If this is done, it is found that W is a maximum when $\beta=\frac{1}{2}$. For this value of β, Equation 14 becomes

$$\epsilon=\frac{i_o^2RX_o}{v}ln\ n \tag{15}$$

where n is the compression ratio or $X_o/(X_o-X)$.

From Equation 12, with $\beta=\frac{1}{2}$

$$R=L_ov/2X_o \tag{16}$$

Substitution of (16) into Equation (15) gives

$$\epsilon=\tfrac{1}{2}i_o^2L_o\ \ln\ n \tag{17}$$

Since the initial energy before compression is $\frac{1}{2}i_o^2L_o$, the energy increase ratio is in n. However, the term ln n does not increase very rapidly with n. More efficient transfer of energy from the explosive to the external load can be obtained by making the load resistor **23** of a sheet of tungsten or tantalum thin enough to heat up during the compression, thereby increasing the resistance and transferring energy to the load.

When R is not constant, Equation 14 cannot be evaluated analytically. Two methods have been used to evaluate this equation with R as a variable. One method used an analog computer; the other involves desk calculations that consisted of dividing the compression into a number of small increments and letting R be a constant in each increment. The successive values of R were calculated from the energy transferred to R in the preceding increment. Both methods gave the same result, the desk calculations served as a check on the computer calculation. Only the computer calculations are discussed here.

It is desired to maximize the energy delivered to the load. The equation for this energy is

$$\epsilon=\int_0^{t_1}i^2Rdt \tag{18}$$

where i and R are variables. The term R has an upper limit determined by the melting point of the material used for the load resistance **14**. For tungsten $R_{max}=12R_0$, and for tantalum $R_{max}=9R_0$, where R_0 is the initial resistance of the load resistance. The compression ratio determines t_1, which, for the computer calculations, is $0.95\ X_o/v$.

The variables i and R are determined by the pair of differential equations

$$\left(\frac{X_o}{v}-t\right)\frac{di}{dt}=\left(\frac{R}{L}+1\right)i \tag{19}$$

and

$$i^2R=\frac{C}{\alpha R_0}\cdot\frac{dR}{dt} \tag{20}$$

Equation 19 is derived from Equation 3, and Equation 20 represents the change in R caused by its heating. Here X_o, v, L, α, and R_0 are constants, C is the heat capacity of the load resistance, and α is the temperature coefficient of resistance in the equation

$$R=R_0(1+aT) \tag{21}$$

where T is temperature.

For these calculations, the constants had the following values:

$X_0=25$ cm.
$v=7\times10^5$ cm./sec.
$L=4.4\times10^{-3}$ h./sec.
$\alpha=0.0045$ ohm/° C. for tungsten.
$\alpha=0.0035$ ohm/° C. for tantalum.
$t_1=3.392\times10^{-5}$ sec.
$i_0=6\times10^4$ amp.

The computer was used to find a value of $C/\alpha R_0$ for a given R_0 such that $R=R_{max}$ at $t=3.392\times10^{-5}$ sec. When this constraint was met, the value of E for that value of

$C/\alpha R_0$ was recorded. FIG. 3 presents ϵ as a function of $R_0/\dot{L}$ for the case of $R_{max}=12R_0$, and ϵ as a function of $R_0/\dot{L}$ for $R_{max}=9R_0$ is presented in FIG. 4.

These figures show that E is a maximum when

$$\frac{R_0}{\dot{L}}\cong 0.1$$

From Equations 18 and 20

$$\epsilon=C\Delta R/\alpha R_0 \qquad (23)$$

For tungsten, with $R_{max}=12R_0$, $\Delta R=11R_0$, and

$$C=\alpha\epsilon/11 \qquad (24)$$

For tantalum, with $R_{max}=9R_0$, $\Delta R=8R_0$, and

$$C=\alpha\epsilon/8 \qquad (25)$$

The energy ϵ in Equations 24 and 25 is the maximum value of the curves of FIGS. 3 and 4, respectively. From the values of R_0 from Equation 22, and C from Equation 24 or 25, the required shape of the load resistance can be determined.

FIG. 3 shows that for the values of i_0, $\dot{L}$, etc. listed above, the energy delivered to a hot tungsten load under optimum conditions is about 1700 j. For a tantalum load resistance, FIG. 4 shows the energy is a little less. Calculations based on Equation 17 show that with the same compression ratio of 20, only 846 j. would be delivered to an optimum constant load.

In comparison tests, capacitor bank **16** was first charged to 3000 v. and then, without a detonator, the firing switch in switching circuit **25** was fired, thus triggering the spark gap switch discharging the capacitors into the field compressor. The result is curve A shown in FIG. 5, which is a photograph of an oscilloscope trace. A detonator was then placed on the field compressor and the capacitor bank **16** was again charged to 3000 v. This time when the firing switch was closed, the spark gap switch discharged the capacitors into the field compressor and the PETN sheet explosive **18** forced the two copper plates **10** and **12** together. The oscilloscope trace of this test is shown as curve B in FIG. 5. The maximum current was 2.8 times that obtained without explosive.

The load resistance **14** forming part of the conducting loop consists of a strip of metal, such as tungsten, tantalum or some similar metal, having high conductivity when cold, but small enough in cross-section and mass so that it is heated to a high temperature and resulting high resistance by the large current in the compressor and strip during the initial exciting pulse and implosion cycles. As the temperature of the strip increases, the resistance increases and the compressor current is transferred to the input load at a predetermined optimum time fixed by the physical parameters and material of the resistor strip, as discussed.

In tests of the magnetic field compressor of FIG. 1 a 0.25 in. thick penta-erythritol tetranitrate (PETN) explosive layer **18** was glued to the top of copper plate **10**, which was spaced 0.75 in. above plate **12**. A steel plate 1 in. thick above explosive **18** partially confined the explosive and therefore increased the detonation pressure on the upper copper plate **10**. Three RG-9B/U coaxial cables **15** attached to the compressor were connected to a 480-μf. capacitor bank **16** which produces the initial field about plates **10** and **12**. An exploding-bridge-wire (EBW) type detonator **20** initiated an explosive delay cord **21**, which in turn initiated the PETN explosive **18** after a 36.5-μsec. delay. This delay allowed the magnetic field in the compressor to reach its maximum initial value before the detonation wave progressing along the length of the explosive layer **18** forced the entire upper copper plate **10** against the lower one **12**. Plates **10** and **12** were 15 in. long, 1.5 in. wide, and 0.070 in. thick. As the compression progressed, current was forced through the temperature sensitive load **14**. The load resistance strip **14** was placed at an angle so that there would be less dead space at the end of the compression when the detonation wave reached the left end of the upper plate **10**. The steel block on which the lower plate was mounted was sufficiently large to withstand the force of the explosion.

The electronic firing switch in switching circuit **25** supplied two simultaneous pulses, each of about 1000 v., from a 1-μf. capacitor. One pulse fired the EBW detonator **20**; the other drove the primary of an air core transformer which stepped up the voltage of the pulse from the firing switch sufficiently to trigger the spark gap switch; thus firing detonator **20** and the spark gap switch simultaneously.

Theoretical and experimental considerations have been given for the optimum choice of strip material and physical dimensions as determined by the material properties, implosion times and electrically defined characteristics of the circuit involved in the field compressor circuit. A detailed analysis of the equations utilized in determining the Energy vs. $R_0/\dot{L}$ curves for both tungsten and tantalum (where R_0 is the initial resistance of the load strip) is given and from these equations and curves, the required optimum dimensions of the load can be determined.

To protect the external output load **23** from blast, it can be positioned a short distance from the field compressor and connected to the compressor by a very low impedance parallel plate transmission line.

The variable resistance shorting strip feature of this invention can be used to furnish high amplitude, short duration current pulses for lasers, pulsed magnets, bursting bridge-wire devices and plasma devices.

If the load resistance **14** are made smaller, the tungsten or tantalum can be vaporized rather than heated to incandescence and make a good source of intense light pulses.

The total magnetic flux in this device is conserved and therefore it is not possible to cascade field compressors to produce larger and larger fields, but it is possible to obtain energy from each stage of a cascaded field compressor as the field is allowed to expand into the next stage.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A magnetic-field compressor system for producing large electric power pulses and for greater energy transfer to an output load comprising:

(a) an electrically conducting loop formed from a pair of spaced-apart highly conducting metal sheets connected together at one end with a strip of temperature sensitive variable resistance material as a load resistance which varies in resistance with time as a function of current induced heating,

(b) an output load connected across said temperature sensitive variable resistance strip,

(c) means for inducing an initial large magnetic field in the space within said conducting loop,

(d) means for explosively compressing together the spaced-apart conducting sheets of said conducting loop when said initial magnetic field is at its maximum value causing a high current across said variable load resistance.

(e) circuit means for initiating said means for inducing an initial magnetic field, and for initiating said means for explosively compressing the conducting loop.

(f) said variable resistance strip shorting out the output load prior to current induced heating and operable to add resistance to the circuit of the conducting loop as the strip is heated to a high temperature by the high current generated in the compressor and strip allowing maximum build-up of current and flux before the resistance of the strip switches the current to an output load, and permit

impedance matching for optimum loading to match desired output load requirements, thus permitting efficient energy transfer to the output load.

2. A system as in claim 1 wherein said means for inducing an initial magnetic field comprises a capacitor bank connected to said conducting loop.

3. A system as in claim 1 wherein said explosively compressing means comprises an explosive layer adjacent one of said metal sheets.

4. A device as in claim 3 wherein said explosive layer is initiated at one end to allow progressive detonation along the length of said conducting loop to progressively reduce the space within the loop.

5. A device as in claim 3 wherein said explosive layer is penta-erythritol tetranitrate.

6. A system as in claim 1 wherein said load is a strip of tungsten.

7. A system as in claim 1 wherein said load is a strip of tantalum.

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