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PULSED POWER FOR ELECTROMAGNETIC LAUNCHING

M. Cowan

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PULSED POWER FOR ELECTROMAGNETIC LAUNCHING*

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ABSTRACT

There are system advantages to producing power for electromagnetic propulsion by real time generation rather than by a sequence of generation-storage-switching. The best type of generator for this purpose is the flux compression generator. Different types of flux compression generator which have been developed at Sandia National Laboratories are reviewed and their applications to electric launching are discussed. New experimental facilities for producing more powerful generators are described and cost comparisons are made.

CONTENTS

	Page
Introduction	7
Electrical Requirements for Electromagnetic Launching	8
Flux Compression Generators	8
New PULSAR Mode for Electromagnetic Guns	14
Free Piston PULSAR for Space Launching	20
Experimental Facilities	21
Cost Estimates for Pulsed Power	26
References	27

ILLUSTRATIONS

1 - Axial mode for PULSAR generator system	10
2 - Radial mode for PULSAR generator system	11
3 - Equivalent circuits for PULSAR	13
4 - Ratio of pulse energy to magnet energy as function of K_{12} for various values of $1/\alpha$	15
5 - MDF PULSAR	16
6 - Equivalent circuits for MDF PULSAR	18
7 - Features of the cryogenic system	22
8 - Two superconducting magnets, 0.4 m and 1.0 m warm bore	24
9 - Windings for superconducting magnets, 1 m and 2 m diameter	25

TABLES

I - Sandia's Helical Generators	23
II - Costs for Pulses of More than 1 MJ	26

Introduction

A generator system is being developed for future particle beam accelerator requirements which also has potential application to electromagnetic launching.^{1,2,3} It is called the PULSAR system and its main components are a superconducting magnet, a generator coil of normal conductor, and an armature which may be a metallic conductor or a plasma. Energy conversion involves magnetic flux compression which is achieved by using chemical energy to increase forcibly the mutual inductance between the armature and the generator coil. The superconducting magnet provides the operating flux but develops only a small current transient during pulse generation and then returns to its initial state. The system lends itself to repetitious generation of pulses. In some operational modes some relatively inexpensive hardware is expended along with the chemical fuel for the generation of each pulse.

Power requirements for electromagnetic launching for military and space applications are well within the range of PULSAR systems which use metallic armatures. Generator performance with metallic armatures can be predicted with codes which have been experimentally verified and superconducting magnet design methodology for metallic armatures has been established.^{1,3}

In this paper the power requirements for electromagnetic launching and PULSAR generator arrangements which are appropriate for this application will be discussed. Experimental facilities which could be applied to electromagnetic launcher development are described and both system and operational cost estimates for high power pulse generators are given.

Electrical Requirements for Electromagnetic Launching

An indication of the electrical power requirements may be developed by assuming that projectiles are launched with constant acceleration. Then the peak power required $P_{\max}$ is given by

$$P_{\max} = \frac{Mv^3}{2\ell\epsilon} \quad (1)$$

where ϵ is the efficiency of the launcher, M and v are the mass and final velocity of the projectile and ℓ is the length of the launcher "barrel". The projectile kinetic energy E is related to the constant magnetic pressure $B^2/2\mu_0$ by the equation

$$E = \frac{B^2}{2\mu_0} A\ell \quad (2)$$

where A is the area of the projectile on which the pressure acts. From Equations (1) and (2) the power requirement may be expressed as

$$P_{\max} = \frac{B^2}{2\mu_0} \frac{vA}{\epsilon} \quad (3)$$

Flux Compression Generators

Meeting the power requirements of electromagnetic launching by real time generation as opposed to the sequence of generation-storage-switching offers potential advantages in system size, complexity, and cost. However, when values for various applications of interest are used for the parameters of Equation (1), one sees that power requirements usually exceed 10^9 W and for some important applications are greater than 10^{10} W.

Flux compression generators are most suitable for providing high power since they come closer to the limit of power that can be generated by moving a conductor (armature) into magnetic field B with velocity v_a .

This limit is expressed as

$$\text{Generator Power Limit} = \frac{B^2}{2\mu_0} v_a \frac{\text{watts}}{m^2} \quad (4)$$

The similarity of this equation with Equation (3) is apparent. This power limit cannot be approached by generators which allow significant flux diffusion through the armature.

Although flux compression generators originally were powered with high explosive and were violently self-destructive, they can be designed to be semidestructive, where only some inexpensive hardware is expended for each pulse, or nondestructive. For example, the PULSAR generator system has operational modes which are either semidestructive or non-destructive. Other examples of nondestructive flux compression generators are the Compulsator and Rotary Flux Compression Generator being developed at the U of Texas under W. F. Weldon.^{4,5}

In Figures 1 and 2 two operational modes of the PULSAR generator system are illustrated schematically. These modes, called axial and radial, respectively, have been demonstrated experimentally with metallic armatures, and lumped parameter equivalent circuit models have successfully anticipated experimental performance.¹ The radial mode is currently being studied for operation with a fast plasma armature.^{6,7}

The feature common to all present nondestructive flux compression generator designs is that the required reduction of inductance in the generating circuit is accomplished by a forced increase in mutual inductance between the armature and stator rather than by a moving point of physical contact between armature and stator which actually removes self-inductance and resistance from the generating circuit.

The latter is always a feature of high gain, self-destructive flux compression generators. Mutual inductance increase is accomplished in the axial PULSAR mode (Figure 1) by passing a cylindrical armature (free piston) of fixed radius axially through the generator coil. This kind of

FREE PISTON PULSAR (AXIAL MODE)

Figure 1 - Axial mode for PULSAR generator system..

PULSAR (RADIAL MODE)

Figure 2 - Radial mode for PULSAR generator system.

generator can be powered by artillery propellant, compressed gas, natural gas, diesel fuel, or gasoline. In large sizes (armature diameter ~ 1 m) it makes very efficient conversion of chemical to electric energy and power output can exceed 10^{10} watts.

In the radial mode (Figure 2) mutual inductance increase is by radial expansion of the armature within the stator. In this case the armature is explosively driven and is relatively fast so that high power and efficiency can be achieved with smaller generators.

A simplified circuit diagram for the PULSAR generator is shown in Figure 3a. The magnet L_3 provides flux which is compressed between the armature L_1 and the generator coil L_2 by an increase in the mutual inductance M_{12} . Unlike the more usual flux compression generator, a pulse is always produced with PULSAR even if there is no flux compression. That is, even if the load-generator circuit has a time constant shorter than the pulse duration. This is due to the fact that the armature L_1 moves into the magnetic field of the magnet at the same time that its coupling with the generator coil L_2 is increasing (M_{13} and M_{12} increase simultaneously). This is a feature which is shared with the Compulsator. In Figure 3b the PULSAR generator equivalent circuit is shown in still simpler form. The voltage $\mathcal{E}(t)$ is the $v \times B$ voltage of the armature as it moves into the magnetic field of the superconducting magnet. The Compulsator has been represented by the same simplified circuit.

The equations of the PULSAR circuits in Figure 3a may be solved to find the ratio of pulsed energy delivered to the load to the energy stored in the superconducting magnet. The result is given in terms of the coupling coefficients K_{12} , K_{13} and K_{23} and $\alpha = L_1/L_2$ as follows:

$$\frac{\text{Pulse Energy in Load}}{\text{Magnet Energy}} = \alpha \left[\frac{K_{12}K_{13} - K_{13}^2 K_{23}}{(1+\alpha)(1-K_{13}^2) + 2K_{12}K_{13}K_{23} - K_{12}^2 - K_{23}^2} \right]^2$$

Figure 3a

Figure 3b

Figure 3 - Equivalent circuits for PULSAR.

Figure 4 shows this ratio of pulse energy to magnet energy as a function of the maximum value of K_{12} for three α values $\alpha = 0.01, 0.1, \text{ and } 1$. Consistent values of K_{13} and K_{23} were used in this example. The curves show that only a fraction of the priming energy originally in the generator is delivered to the load unless the coupling coefficient K_{12} can reach values of $K_{12} > 0.9$. Also, this simplified analysis neglects flux losses. In addition, to keep the output relatively high, one must operate reasonably close to the optimum value of α which for realistic values of K_{12} is $\alpha = 0.1$.

Unfortunately, low energy gain is a feature of flux compression generators which use forced increase of mutual inductance rather than a moving point of physical contact between armature and stator to generate the pulse. They are still attractive if the initial priming energy is supplied by an inductive store because of the low cost of inductively stored energy.

The PULSAR system may be viewed as a scheme to utilize an inductive store for generating pulse power where no opening switch is required and where it is not necessary to recharge the store for each pulse.

New PULSAR Mode for Electromagnetic Guns

For military electromagnetic gun applications it is important to make the size and mass of the power supply as small as possible. Also, for the rail gun it is desirable that the power supply deliver nearly constant current, but increasing power. A concept for a new operational mode of the PULSAR system called the MDF Mode has been developed which will greatly reduce generator size required for a given pulse energy and which will come close to the desirable features for rail gun power. This is accomplished by using a moving point of physical contact between armature and stator for forced reduction of inductance in the load circuit. In this mode flux compression generators can make large energy gains. This may be done in the PULSAR system by a method which is virtually nondestructive. The generator geometry is illustrated in Figure 5. The high explosive fuel is in the form of copper or

Figure 4 - Ratio of pulse energy to magnet energy as function of K_{12} for various values of $1/\alpha$

MDF PULSAR

Figure 5 - MDF PULSAR

aluminum mild detonator fuse (mdf). The mdf is wound into a coil of n turns on a low density foam mandrel. This winding serves as both the fuel cartridge and generator coil and is the only hardware expended for each pulse. The winding is formed by a number of mdf pieces or wires in parallel, the number being consistent with the number of turns desired, the necessary spacing between the mdf wires, and the circumference of the mandrel. The mdf fuel cartridge is positioned within the magnet and also inside a thick-walled steel blast shield which serves additionally as the stator. One end of the mdf wires is connected to the stator through the load; the other is connected to a ring detonator. When the mdf is detonated the wires "unwind" and move through the gap between the cartridge and stator, contact the stator to complete the circuit, and ultimately eliminate all the inductance and resistance of the mdf winding from the load circuit.

The simplified equivalent circuits for this PULSAR mode are shown in Figure 6a. In this case L_2 is reduced to zero during operation as are M_{12} and M_{23} . The equations for these circuits have been solved for the ratio of load energy to magnet energy assuming L_ℓ is constant and the result is

$$\frac{\text{Pulse Energy in Load}}{\text{Magnet Energy}} = \left(K'_{23} \right)^2 \frac{L'_2}{L_\ell}$$

Where the primes indicate the initial value of K_{23} and L_2 . This shows the possibility of energy gain with reasonable values of K_{23} since it is possible to have large values for L'_2/L_ℓ .

In Figure 6b a single equivalent circuit is shown with a time-dependent inductive load $L_\ell(t)$ which represents an electromagnetic rail gun.

The equation for the circuit of Figure 6b is as follows

$$\frac{d}{dt} (LI) + IR = \mathcal{E} \quad (5)$$

where $L = L_{\text{mdf}} + L_\ell$

Figure 6a

Figure 6b

Figure 6 - Equivalent circuits for MDF PULSAR.

Using the dot notation for derivative with respect to time the equation may be expressed in the following form

$$\frac{\dot{I}}{I} = - \frac{\dot{L}}{L} \left(1 + \frac{R}{\dot{L}} - \frac{\dot{\mathcal{E}}}{IL} \right) \quad (6)$$

It is apparent from this form that the requirement for constant current is

$$\frac{\dot{\mathcal{E}}}{IL} - \frac{R}{\dot{L}} = 1 \quad (7)$$

which can be rewritten as

$$\dot{\mathcal{E}} - IL = IR \quad (8)$$

Since $\dot{L}$ is given by $\dot{L} = \dot{L}_{\text{mdf}} + \dot{L}_{\ell}$ and $\dot{L}_{\text{mdf}}$ is negative while $\dot{L}_{\ell}$ is positive, Equation (8) may be rewritten using absolute values for $\dot{L}$ as follows

$$\dot{\mathcal{E}} + I\dot{L}_{\text{mdf}} = IR + I\dot{L}_{\ell} \quad (9)$$

If the resistance R is primarily in the mdf winding, R could be made to decrease linearly with time to compensate for the linear increase of $\dot{L}_{\ell}$ in the rail gun. A linearly increasing fraction of the total voltage would be applied to the rail gun. Then, if Equation (9) is realized experimentally, the requirement for constant current and increasing voltage for the rail gun is satisfied. It seems likely that this could be accomplished reasonably well with simple designs.

This PULSAR system would also produce the relatively long multimilli-second pulses required for rail guns since the voltage $\dot{\mathcal{E}}$ is always generated and the mdf length could be tens of metres. This is a crucial advantage over flux compression systems that do not use

inductive storage for the priming energy. For mdf cartridges wound with low pitch, the value of $\dot{\mathcal{E}}$ would be close to Bgv_d where B is the magnetic flux density supplied by the magnet in the gap of dimension g between the cartridge and stator, and v_d is the detonation velocity of the mdf. Since $v_d = 8.2 \times 10^3$ m/s and the values of B and g can be at least 10 T and 10 cm this voltage can be 10 kV. An additional voltage $\dot{I}L_{\text{mdf}}$ would also be generated as shown by Equation (9).

Free Piston PULSAR for Space Launching

One of the most compelling potential applications of electromagnetic launching is for transporting material into space. The promise is that both cost and environmental impact could be far less than for present methods. Park and Bowen were apparently the first to consider seriously the possibilities of earth-based EM space launching.⁸ The application was for disposal of nuclear wastes. An interesting use of their analysis was made by Peter Mongeau who computed the energy requirements vs mass for reaching escape velocity with vehicles of various diameters.⁹ Peter Mongeau's calculations showed that vehicles of surprisingly small mass could escape successfully with reasonably low initial velocity. For example, a 25 kg mass with initial velocity of 18 km/s could get through the atmosphere and still have the required escape velocity of 12 km/s. A fraction of the initial mass would be lost to ablation but a much larger fraction would escape than for present methods. Using the numbers of this example in Equation (1) we find that the maximum power required times barrel length is given by $\epsilon l P_{\text{max}} = 7.2 \times 10^{13}$ W-m. With mass driver efficiency $\epsilon \sim 1$ and a long barrel ~ 5 km which would be acceptable for this application the required P_{max} is $P_{\text{max}} = 1.4 \times 10^{10}$ W.

Free piston PULSAR generators (Figure 1) which produce this level of power have been considered for commercial power generation.^{1,10} For the space launching application the same generators could be used in a much simpler system than that required for continuous power generation. The following list gives the main design features which have been developed for one such generator.

In this example two generator coils and two oppositely directed armatures were used to balance momentum.

Cylinder diameter, generator coil and magnet lengths	2.85 m
Magnet energy	120 MJ (2 each)
Armature length	3.15 m (2 each)
Armature mass	5.4×10^4 kg (2 each)
Armature velocity (entrance)	135 m/s
Armature kinetic energy (entrance)	984 MJ
Armature velocity (exit)	112 m/s
Armature kinetic energy (exit)	675 MJ
Pulse energy	282 MJ
Pulse duration	25.6 ms
Average pulse	1.1×10^{10} W

For the launching application, compressed air or natural gas combustion could drive the armatures with the exit kinetic energy being used to help compress the air or air-fuel mixture for the next launch. Since the energy requirement for the vehicle in the example above is 4×10^9 J, several generators of this kind would have to be distributed along the barrel.

Experimental Facilities

The present PULSAR generator development program at Sandia National Laboratories has the objective of terawatt power levels in a non-destructive operational mode. For this purpose very fast (20 km/s) plasma armatures are being developed along with an MHD code to anticipate generator performance.

The Electromagnetic Facility where the work is carried out is newly equipped with a helium liquefier and a closed cryogenic system. It is now unique in being able to deal with high explosive and large superconducting magnets in the same experiment. Figure 7 shows the Electromagnetic Facility with most of its cryogenic features indicated.

Figure 7 - Features of the cryogenic system: A. helium compressors, B. liquid nitrogen, C. gaseous helium, D. helium liquifier, E. helium storage dewar, F. control dewar, H. helium transfer line. Other features: G. three 200 kJ - 20 kV capacitor banks, I. 1-m magnet, J. recoilless cannon, K. two explosive generators operating in parallel into protected load.

Two superconducting magnets are available for experiments. One, with an 0.4 m warm bore, stores 200 kJ and has been used for all PULSAR experiments to date. The other has a 1.0 m warm bore, is able to store 300 kJ, and is just becoming operational. In addition, we have the winding for a third magnet which will be ready for experiments in 1982. This one has a 2 m warm bore and stores 2 MJ. Figure 8 shows the 0.4 m and 1.0 m magnets. Figure 9 shows the windings for the 1.0 m and 2.0 m magnets.

We expect that an MDF PULSAR system based on the 1 m magnet would be able to generate pulses in excess of 1 MJ with power $>10^9$ W.

In addition to three capacitor bank modules each of 200 kJ - 20 kV, helical explosive generators (self-destructive) in three different sizes are available off-the-shelf for use at the Electroexplosive Facility. These are well-known and dependable power sources adaptable to a wide range of load, but are relatively expensive to use. Table I lists the physical and electrical features of these helical generators.

Table I - SANDIA'S HELICAL GENERATORS

Generator Model	106	169	612
Length (in)	17	25	31
Inner Diameter, Coil (in)	6	9	12
Weight (lb)	23	61	108
Explosive Weight (lb)	5	17	37
Inductance (μ H)	4.7	18.1	3.5
Operating Time (μ s)	28	45	55
e-Folding Time (μ s)	5	7.5	10
Saturation Current (MA)	3	7	12
Max Experimental Energy (MJ)	0.6	1.6	2.6
Estimated Maximum Energy (MJ)	0.6	1.6	5.0

Figure 8 - Two superconducting magnets, 0.4 m and 1.0 m warm bore

Figure 9 - Windings for superconducting magnets, 1 m and 2 m diameter

Cost Estimates for Pulsed Power

Table II gives estimated system and operational costs of pulsed power for the kind of power sources which have been discussed. Operational costs only include the cost of the fuel and hardware expended.

Table II - COSTS FOR PULSES OF MORE THAN 1 MJ

Type of Generator	System Cost	Operational Cost
Self-destructive		
Single Stage Helical	$\$10^5 - \10^6	1¢/J
Cascaded Helical	0	Few ¢/J
Nondestructive		
PULSAR (PLASMA)	10¢/J	0.1¢/J
PULSAR (MDF)	<1¢/J	0.1¢/J
PULSAR (FREE PISTON)	Few ¢/J	10^{-6} ¢/J

Self-destructive helical generators require a facility for providing their priming energy if they are operated in a single stage mode.

Several stages may be cascaded to eliminate the need for such a facility, but the operational cost is higher when this is done. The load can usually be protected and used repeatedly even with self-destructive generators.

Operational costs for PULSAR generators which use high explosive for fuel (the Plasma and MDF modes) are based on costs we pay for experimentation and could be expected to be much lower if a large number of explosive fuel elements were produced. For example, we pay \$320/lb for explosive in the form of mdf but material costs are less than \$30/lb.

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