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L.L. Altgilbers
U.S. Army Space and Missile Defense Command
P.O. Box 1500, Huntsville, AL, 35748
Larry.altgilbers@smdc.army.mil

Recent Advances in Explosive Pulsed Power

Contents

Abstract

Within the last 5 years there has been renewed interest in explosive pulsed power with programs springing up at institutions in several countries as well as a revival of programs in countries that have a history in this field. As a result, there have been several advances in our understanding of the physics of these devices, which will be discussed in this paper. Most of the advances were the result of a Multidisciplinary University Research Initiative and a New World Vista Program sponsored by the Air Force Office of Scientific Research (MURI). Other advances have come from Loughborough University in the United Kingdom, companies such as Diehl and Rheinmetall in Germany, and government laboratories such as the Agency for Defense Development in South Korea. The most persistent research on most of these devices was done by A.B. Prishchepenko and his team, V.E. Fortov at the Institute of Chemical Physics, and All-Russian Institute of Experimental Physics (also known at VNIIEF or Arzamas-16) in Russia with work continuing today. In this paper, recent advances in seven types of explosive driven pulsed power generators will be presented.

1. Introduction

Explosive-driven pulsed power can be traced back to the 1940s and is an outgrowth of the nuclear weapon programs in the United States, United Kingdom, and the Former Soviet Union [1]. Explosive pulsed power systems have several advantages including one of the highest energy storage densities and as a result they can be made very compact and lightweight. Their major disadvantage is that they are typically single shot. Therefore, whether or not explosive pulsed power is applicable will depend on its intended use. Since several new applications have been identified for explosive pulsed power, recent advances in their development will be presented.

There are basically seven types of explosive power supplies [2] that were developed in the ensuing years:

- Magnetocumulative Generators (MCGs) also referred to as Magnetic Flux Compression Generators, or simply Flux Compression Generators.
- Explosive Magnetohydrodynamic Generators (EMHDG).
- Ferroelectric Generators (FEGs) also referred to as Piezoelectric Generators (PEG).
- Ferromagnetic Generators (FMGs).
- Moving Magnet Generators (MMGs).
- Shock Wave or Semiconductor Generators (SWG).
- Superconducting Generators (SuG).

A brief description of each generator will be presented along with a summary of recent advances.

All of these generators work on the principle of converting the chemical energy into electrical energy. Three of the generators (MCG, EMHDG, and MMG) are based on the motion of a conducing medium through a magnetic field, while the PEG and FMG are based on phase transitions (polarized-to-depolarized and magnetic-to-demagnetized states, respectively). A variant of the MCG that utilizes a phase transition is the semiconductor MCG. Unlike classical MCGs, where compression takes place in air or gas such as SF6, the compression takes place in a solid crystal such as CsI or a powder such as oxidized Al. Shock pressures will cause the dielectric to transition into a metallic state that takes the place of the metal liner. The advantage of this is that the liner instabilities observed in classical MCGs do not occur in this variant [3]. Another variant of the MCG is the superconducting generator, which is also based on a phase transition; that is, the transition from a superconducting to a non-superconducting state. While the semiconductor generator was first studied in Japan [4] in the 1980s, most of the work since then on this generator has been carried out by A.B. Prishchepenko [5] and by E.I. Bichenkov [6] in Russia.

Of the seven generators mentioned above, the most studied and, thus, the most developed and the most reported on is the classical MCG. Despite over fifty years of development, researchers continue to learn about the capabilities and the limitations of MCGs, especially miniature generators (minigens). The development of the other six types of generators has been rather sporadic, but yet there have been some recent developments.

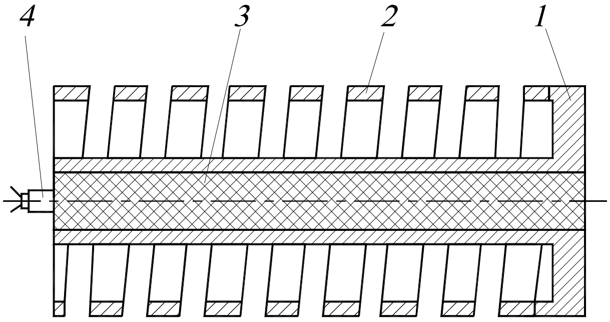

Fig. 1. Helical (spiral) magnetocumulative generator: 1 – linear; 2 – helical coil; 3 – explosives; 4 – detonator.

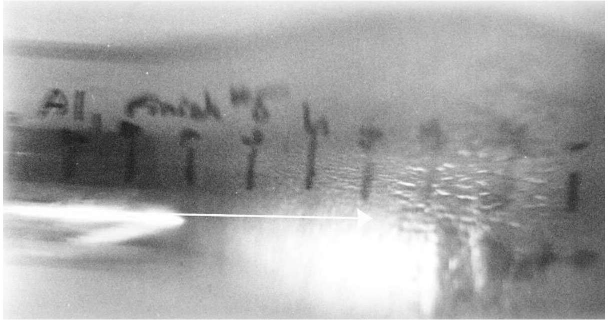

Fig. 2. "Bulbing" effect during early stages of armature expansion (courtesy of the University of Missouri Rolla).

2. Magnetocumulative Generators

The helical MCG (Fig. 1) consists of a seed source (prime energy source for creating the initial magnetic field within the generator), a helical coil called a stator, concentric coaxial metal tube filled with high explosive called an armature, output circuit, and load [2,7]. When the explosive charge is detonated, the armature expands at one end forming a conical glide plane that moves along the length of the generator shorting out the turns of the helical coil and compressing the magnetic field. These generators can be classified based on the geometric shape of their conductors; that is, the stator and armature. These include cylindrical, helical, plate, strip, disk, loop, and bellows generators. The cylindrical generator is used to generate high magnetic fields, while the rest are mostly used to generate high electrical currents and energies.

Two of the most recent advances in classical MCGs are development of

1. an understanding of the behavior of the armature material during early expansion and
2. miniature generators (*minigens*).

It was long known, that the armature at its detonator end had to extend at least two diameters out beyond

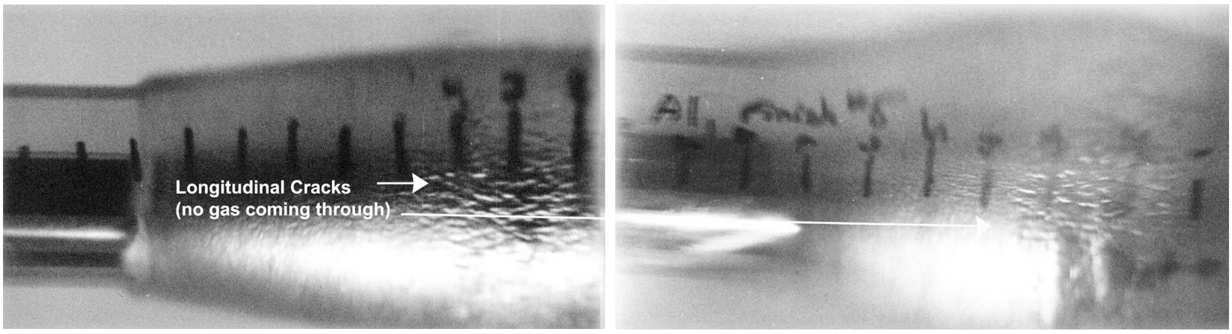

Fig. 3. Rupture formation on the outer surface of an expanding armature during early stages of expansion (courtesy of the University of Missouri Rolla).

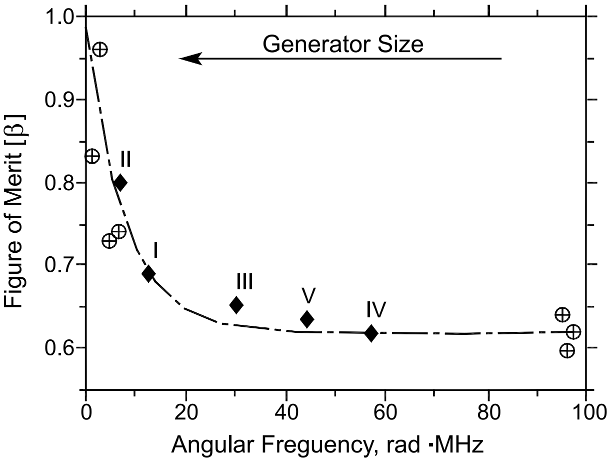

Fig. 4. Dependence of the figure of merit on the contact point's angular frequency for FCGs with a constant diameter armature.

the end of the stator to get good generator operation. Recent work at the University of Missouri in Rolla (UMR) has revealed that two things occur at the detonator end of the armature [8,9]. The first is that the armature tends to form a "bulb" like shape (Fig. 2) since the initial detonation wave is spherical in shape and it takes at least a distance of two diameters of the armature for the armature to form a conical glide plane. This "bulbing effect" prevents good crowbarring of the armature with the stator, which means that there will be flux loss. In addition, a rupture (Fig. 3) forms on the outer surface that propagates along the length of the armature to the spot where this transition to the conical glide plane occurs. This fracture is thought to be due to shock waves, not the expansion of the metal due to the detonation. Mach stems were predicted to form in the region where longitudinal fracturing stopped. Mach stems alter the pressure distribution next to the explosive-tube interface, which causes the detonation wave to lose contact with the interface at about the same point the longitudinal fracturing stops.

Minigens has been defined to be generators with an overall diameter less than 40 mm [10]. Texas A&M University (TAMU) and Texas Tech University (TTU) have undertaken a systematic study of these generators including seeding them with permanent magnets and capacitor banks, using different types and shapes of construction materials, and using different designs such as various combinations of straight and tapered stators and armatures. In order to compare these different types of generators, a *figure of merit*, α, was introduced. It is defined by the following formula:

$$G_I = \left(\frac{I_f}{I_0}\right)_{Experimental} = \left(\frac{L_G + L_l}{L_l}\right)^{\alpha}_{Ideal}, \quad (1)$$

where the initial current is I_0, the final current is I_f, the initial generator inductance is L_G, and the load inductance is L_l,. It was found that as the diameter of the MCG decreased, its figure of merit also decreased (Fig. 4). While it is possible to get current gain from the small generators, it is not possible, using the current designs, to get energy gain. Methods for improving the performance of minigens are now under investigation. The results of the TAMU and TTU studies can be found in [11–14].

In summary, TAMU [11,12] found that, in general, both large and small generators perform better with larger wire size or larger conductors. This is due to the reduction of current densities on the conductors, with an associated reduction in magnetic flux loss. Small and large generators both perform better with round wire, rather than square wire, since the edges of the square wire tend to promote electrical breakdown. Also, all FCGs exhibit better performance as the inductive loading increases.

In two areas, the smaller FCGs show somewhat different characteristics from the larger generators. The first of these is the realized experimental gain, relative to the ideal gain of the unit. The small generators tested to date appear to be limited to current gains of a few ten's, at most. This result is reflected in the lower figure of merits that have been measured for these FCGs. Another difference is that

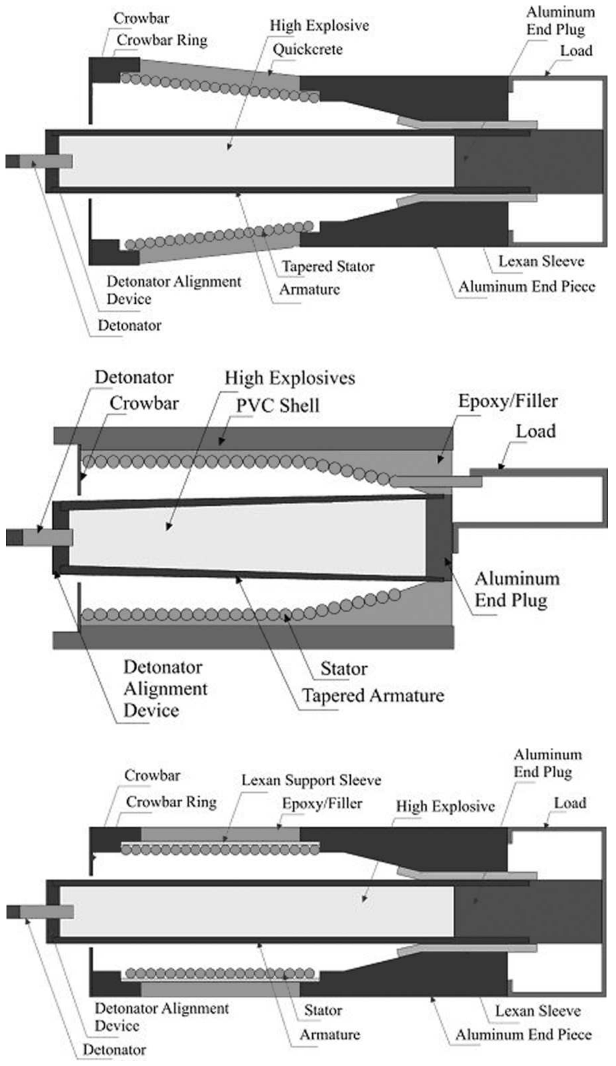

Fig. 5. Different tapered MCG designs (courtesy of Texas Tech University).

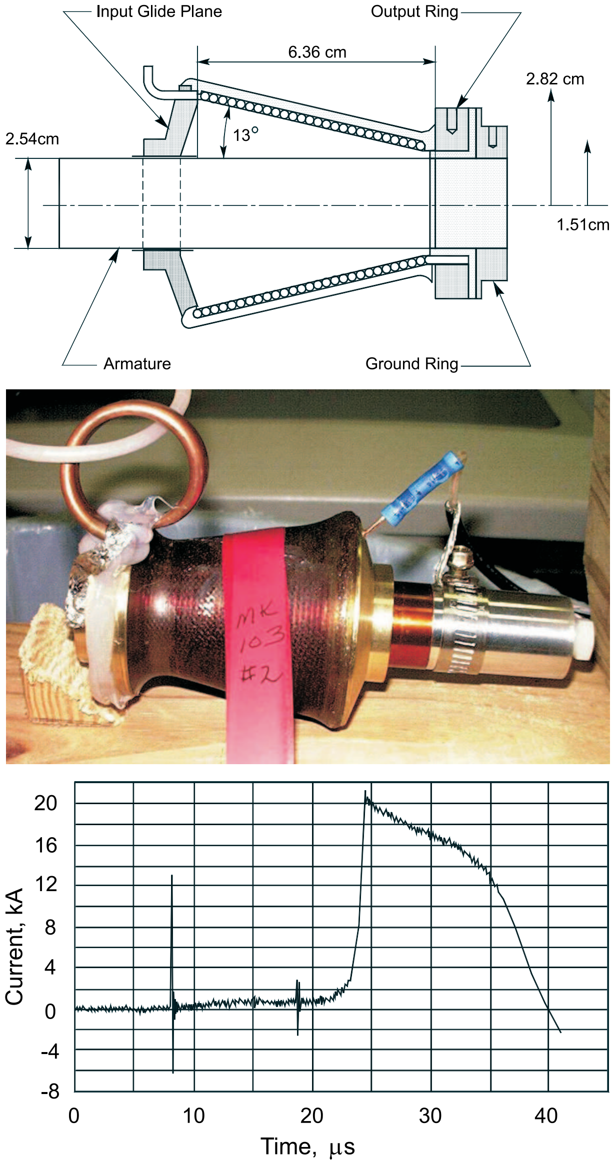

Fig. 6. Diagram (top), photograph (middle), and representative output waveform (bottom) of the Texas A&M Mark 103 tapered MCG (courtesy of Texas A&M University).

higher current loading in the small generators tend to show improved performance figures of merit until current saturation effects become significant. It has been speculated that this may be due to a better connection being formed between the armature and stator, perhaps due to higher internal voltages.

To understand the losses in these small generators, TTU and TAMU (Figs. 5 and 6) investigated a tapered modification of their simple constant diameter inch size generators [12,14]. They have observed two types of losses in FCGs: ohmic losses due to the finite resistance of wires and armature materials and intrinsic flux losses, which may be unrecoverable flux trapped in the conducting layers of the generator components and thus lost for compression. It was concluded that the constant diameter FCGs exhibited more intrinsic than ohmic losses (69 % compared to 16 %, respectively), while the tapered generator with the same stator dimensions and tapered armature exhibited less intrinsic and more ohmic flux losses (13 % compared to 66 %, respectively). There are ongoing efforts to reduce these losses and to increase both the current and energy gains of these small generators.

Texas Tech has also recently built and tested a helical MCG for driving high inductance loads. Simple MCGs can produce several hundred kiloamps, but only voltage levels less than 10 kV. Many loads require less current and higher voltages. In order to meet this need for loads with inductances of several microhenries, TTU developed a multistage MCG. They built and tested a dual sage MCG with a total length of 250 mm, a helix inner diameter of 51 mm, which was wound on Teflon insulated stranded wire of different sizes in the range from AWG 12 to AWG 22

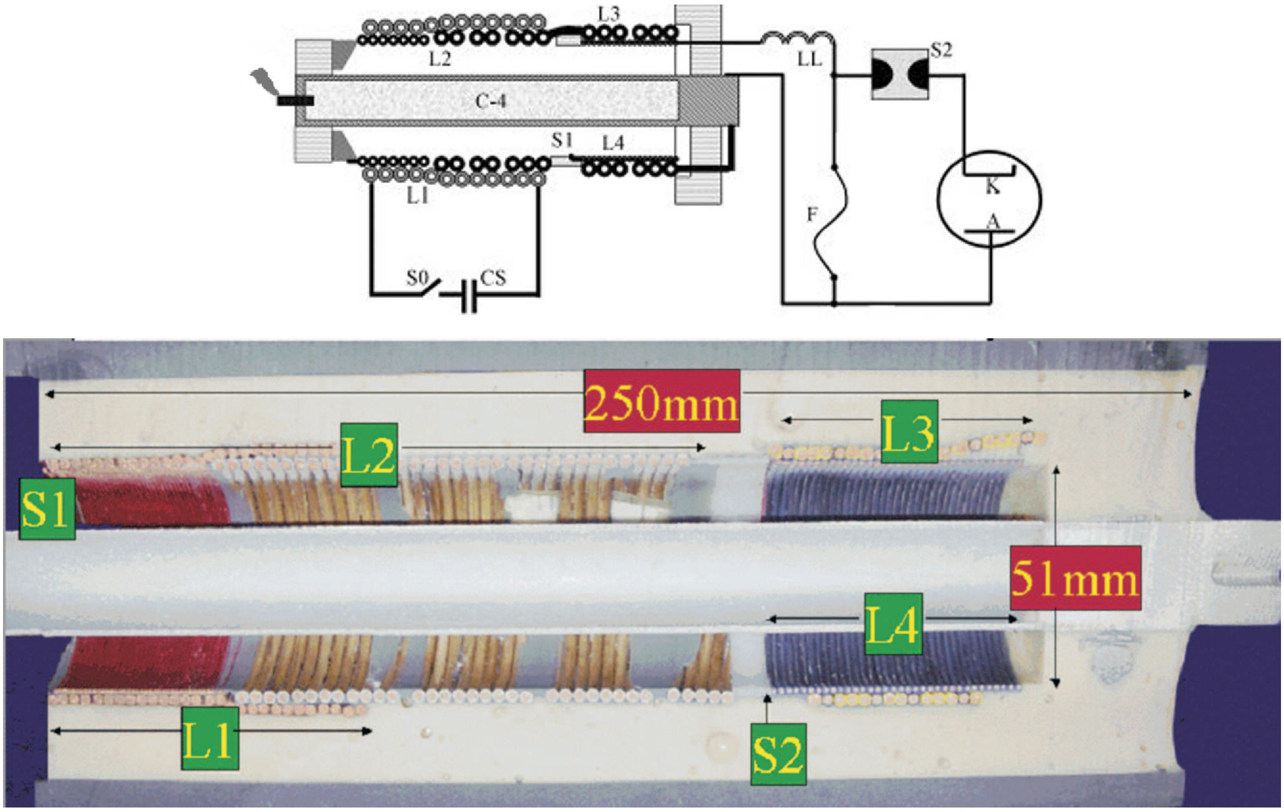

Fig. 7. Texas Tech staged MFCG connected to an inductive load, LL. Storage capacitor (50 μF) – CS, Closing switch – S0, field coil for first stage – S1, Crowbar for L2 - L1, first stage coil - L2, primary of dynamic transformer – L3, Crowbar for L4 – S2, secondary of dynamic transformer – L4. See Table 1 for specific helix dimensions. (Courtesy of Texas Tech University).

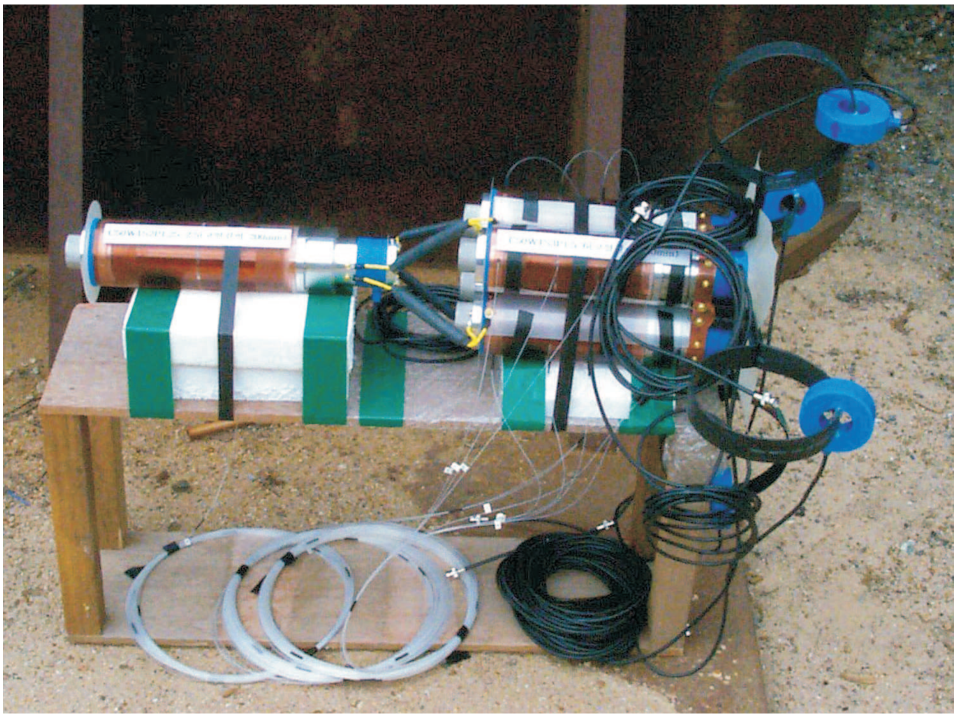

Fig. 8. Serially and Parallel connected FCGs developed by the Agency for Defense Development, Taejon, South Korea.

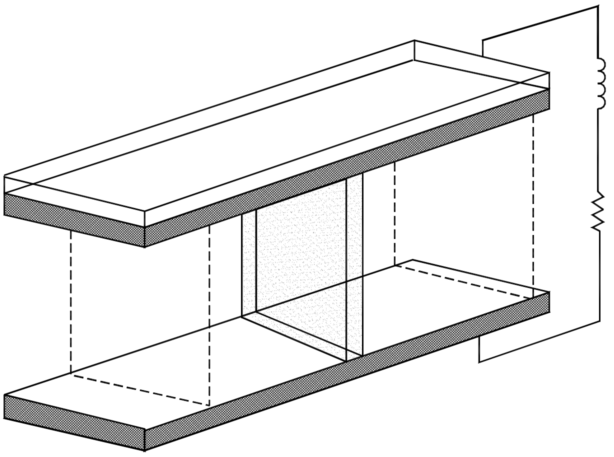

Fig. 9. Generalized MHD generator circuit.

(Fig. 7). Dynamic flux trapping was used to capture the flux and deliver it from the first stage into the second stage. A transformer was built into the output circuit of the generator to deliver the energy to the load. This generator had an energy gain of 13 into a 3 μH load, delivering an energy of 1.5 kJ. The gain of the overall generator was about 30 stages, when they were separately tested.

In South Korea, the Agency for Defense Development has worked a number of years on helical MCGs. More recently they have cascaded MCGs, Fig. 8, in series [16] and in parallel [17]. Using a capacitor bank as the seed source, they serially connected two MCGs, each with an initial inductance of about 45 μH, to drive a 136 nH load. They also used a capacitor bank to seed a single MCG, which was then used to seed four MCGs. They found that the energy multiplication was dependent on the ratio of the initial inductance to that of the load inductance and that the output voltage across the load increased as the number of MCGs increased. They also used a capacitor bank to seed two MCGs in parallel and a capacitor bank to seed a single MCG that seeded four MCGs in parallel. They found that the load voltage was almost constant regardless of the number of MCGs in parallel provided the initial current and load inductance were kept the same and that differences in the activation time between MCGs connected in parallel caused severe distortions of the dI/dt waveform due to the different load inductance felt by each MCG. Reduction in output energy caused by a 1 μs jitter was as high as 12 % for two MCGs in parallel.

In addition to the experimental work, several relative simple but successful computer codes that model MCG operation have been developed. All these newer codes are Windows based and work on the personal computer. They include the Texas Tech code [18], a zero dimensional code developed by Loughborough University [19], and a lumped circuit code developed by Scientific Application International Corporation (SAIC) [20]. All these codes were designed to model only the helical MCG. Loughborough University has also developed one and two dimensional codes for the helical MCG [21]. There is one commercial code available for helical generators called CAGEN [22]. The most general purpose code that can model most types of generators is SCAT developed at Los Alamos National Laboratory [23].

3. Explosive MHD Generators

In the explosive magnetohydrodynamic generator (EMHDG) (Fig. 9), an explosive charge is use to create a plasma, which is then propelled between two metal plates immersed in an external magnetic field. As the plasma passes between the plates, the magnetic field causes the ions to move towards one plate and the electrons towards the other plate. The charge that collects on these plates is delivered by an external circuit to a load. The first paper on EMHDGs was published in 1963 [24]. The objective of this original research was to replace the metal liner in conventional MCGs with a plasma liner and create a source of electrical current that was not destroyed. The EMHDG can be thought of as a flat MCG in which the metal liner is replaced by a compact conducting plasmoid formed behind a shock wave in the head of the explosive flow. Unlike the MCG, the EMHDG can generate a series of powerful electric pulses.

In the early 1960s, MHD generators were thought to be a thermodynamically more efficient source of commercial electric power [25–27]. However, it was soon recognized that propellant and explosive driven MHD generators could be an efficient, small scale source of pulsed power. Other advantages included possible

1. impedance matching to a wide range of loads,
2. choice of pulse lengths ranging up to one or two milliseconds,
3. multiple shots, and
4. higher conversion efficiencies.

By the 1980s, the Russians [28,29] were world leaders in this area, although there had been some work done in the US [30], Japan [31], England [32], and South Korea [33]. Since the recent Russian work is documented in two monograms [28,29], this section will briefly summarize some of the more recent work on explosive driven MHD generators done in the UK, US, South Korea, and Japan.

In conventional MHD generators, a plasma flows between two parallel rectangular electrodes and a magnetic field applied perpendicular to both the plasma flow and electrodes generates an electromotive force (EMF) by means of the Faraday Effect. In EMHDGs, this plasma is created by detonating an explosive charge. In addition to the Faraday generator, just described, there are the Hall generator consisting of multiple pairs of opposing electrodes that are shorted together and the output of which is generated in a single load across the first and last of these pairs, the disc generator in which the ionized gas flow is injected at its center and expands radially, and the electrodeless generator.

As the plasma travels along the electrodes, the inductance of the circuit changes. In the mid 1990s, Loughborough University in the UK proposed an unconventional electrode arrangement to enhance these changes to greatly increase the induced voltage with a corresponding increase in the generator's output [32]. They proposed to replace one or both of the electrodes with a helical constant pitch coil. This would increase the duct inductance and its time rate-of-change. They predicted that a five-fold increase in the inductance would increase the output current from a conventional MHD generator from 75 kA to 157 kA.

Loughborough also built and tested a single-shot disposable EMHDG [32]. The generator consisted of a wooden Faraday duct, copper electrodes, and copper type wound magnet. A hollow tube of plastic explosive, when detonated at the top, progressively compresses an air column length wise and expels it as a highly conductive jet traveling at 10 km/s. A capacitor was discharged at a time that would yield a maximum magnetic field at the moment the jet arrived. A detonator crowbar was used to trap the magnetic energy in the coil. Power densities on the order of 1 TW/m^3 were achieved. Since the explosive products following the plasma pulse can be highly insulating, this device possesses an internal opening switch.

The Air Force Research Laboratory (AFRL) has investigated EMHDGs since the mid 1960s [30]. In the 1990s, they built and tested a device capable of generating 1.8 GW of electrical power. They used 2 pounds of explosives to compress, heat, and ionize argon gas via a shaped charge liner in a cavity. A Mylar diaphragm ruptured with the force of a shock wave and forced the argon to flow into a evacuated Lexan shock tube that served as the MHD channel. An electromagnet was energized by a capacitor bank to produce a peak field during the main flow of the gas. Voltages up to 30 kV were generated. A larger scaled generator was built and tested to determine if a larger rectangular shock tube would allow higher voltages and with similar currents. A voltage of 95 kV and power of 23 GW was expected to be generated.

In the mid 1990s, Y. Kakuate et al [31] in Japan used an EMHDG to provide seed current to an MCG. A capacitor bank was used to generate a 2.0 T magnetic field in the EMGDG, which generated an output current of 100 kA. The MCG amplified this current by a factor of 7.6. The output current of this hybrid system was 480 kA.

The Agency for Defense Development (ADD) in South Korea recently completed a study on the effects of load resistance and inductance on EMHDG operation [33]. Explosive driven annular tubes filled with argon were used as the plasma generator. An experimental PBX explosive, weighing 1.2 kg, was used. The MHD channel was made from 1 inch diameter Lexan tube and four sets of Faraday generators. Each Faraday generator consisted of two permanent magnets and two copper electrodes. The load resistance varied from 1.2 to 100 mΩ and the load inductance varied from 0.15 to 36 nH. From the experimental results, it was concluded that

1. the output voltage was very insensitive to the load resistance and inductance,
2. the output current decreased exponentially as the load inductance and resistance increased, and
3. load inductance has greater impact on output current than does the load resistance.

These last two generators were being considered as potential seed sources for MCGs, but indications are that this is not feasible and work is now focused on other devices such as the FMG and PEG (FEG) for the seed source.

A more recent effort has been to combine a Pulse Detonation Rocket Engine (PDRE) with an MHD nozzle and channel [34] to provide on-orbit power generation and maneuverability. A conventional MHD generator design applicable to space operation consists of a rocket-MHD system in which the combustion of the reactants in the rocket combustion chamber elevates the gases to sufficient temperatures for high electrical conductivity by thermal, equilibrium ionization. To facilitate ionization, it is also generally necessary to seed the gases with a chemical compound containing one of the alkaline metals such as cesium, sodium, or potassium. This work consists of replacing the constant-pressure combustion mode of a rocket by a constant-volume combustion process, which is achieved by repetitive cycling of a PDRE. The PDRE is a design variation of the pulse detonation engine (PDE), with a converging-diverging nozzle and stored fuel and oxidizer. The PDRE operates by rapidly filling a combustion chamber with reactants and then igniting the gases in a sufficiently energetic fashion to rapidly initiate a detonation within the chamber. This offers an advantage over conventional combustion systems because the chemical energy is released within a very narrow region behind the detonation wave, thereby forcing the combustion process to occur at near-constant volume conditions. Constant volume combustion yields a higher post combustion temperature than the constant pressure process and

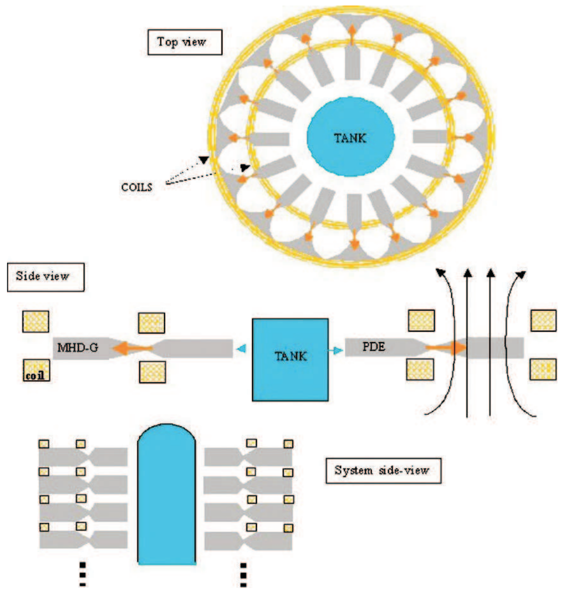

Fig. 10. Different tapered MCG designs (courtesy of Texas Tech University).

a resulting higher degree of ionization. Subsequent blowdown of the hot combustion products through the nozzle yields a high velocity gas with a higher conductivity than that of a conventional rocket engine. Therefore, the PDRE appears to be ideally matched for MHD pulse-power generation.

The PDRE operation does not require extreme pressurization of the gases prior to filling the combustion chamber as with a conventional rocket chamber since most of the pressurization is achieved by the detonation. There is no need for large turbopumps, as moderate propellant pressurization is sufficient. This provides another improvement in generator efficiency since a smaller fraction of the generated power must be used to operate the turbopumps. Robust and fast-acting valves capable of rapidly filling the combustion chamber are the main engineering requirements. The throat between the chamber and nozzle must also be sufficiently small so that gas losses during chamber filling are small. It turns out that this requirement also benefits MHD power generation. A small nozzle throat diameter and a large nozzle exit-to-throat area ratio implies rapid nozzle expansion. Thermal nonequilibrium is then likely to occur within the nozzle. This tends to keep electron temperature and gas conductivity at high levels, while the high expansion area allows for maximum power extraction for a given magnetic field.

A schematic of the system design is shown in Fig. 10. The design is remarkably simple:

1. no active cooling is required;
2. it is modular and failure tolerant;
3. it is robust (i.e., relatively insensitive to shape and field variations; and
4. the nozzle to the PDRE chamber also serves as the MHD generator.

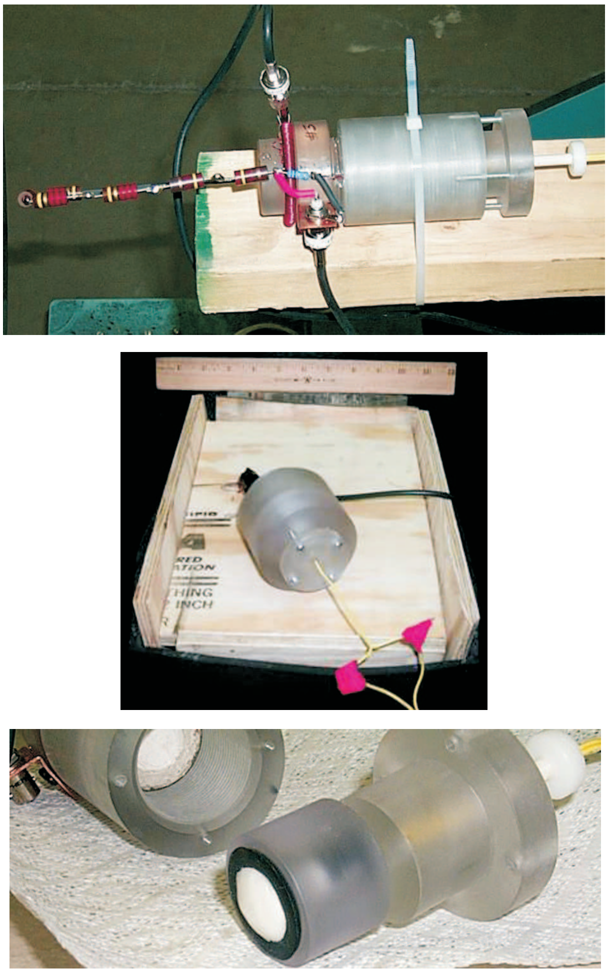

Fig. 11. Photographs of the TTU ferroelectric generator (courtesy of Texas Tech University).

4. Ferroelectric (Piezoelectric) Generators

Explosive driven FEGs have been under development since the mid 1950s [35]. Most of the original work was done using lead and barium titanate and lead zirconate ceramics as the working body. Most of the recent work has focused on the use of lead zirconate titanate (PZT), but there is interest in piezo polymers such as PVDF. The lack of progress in working with these polymers is due to the fact that there are currently no methods for producing large quantities of uniformly polarized sheets of these materials.

Ferroelectric generator (Fig. 11) operation is based on the sudden depolarization of ferroelectric

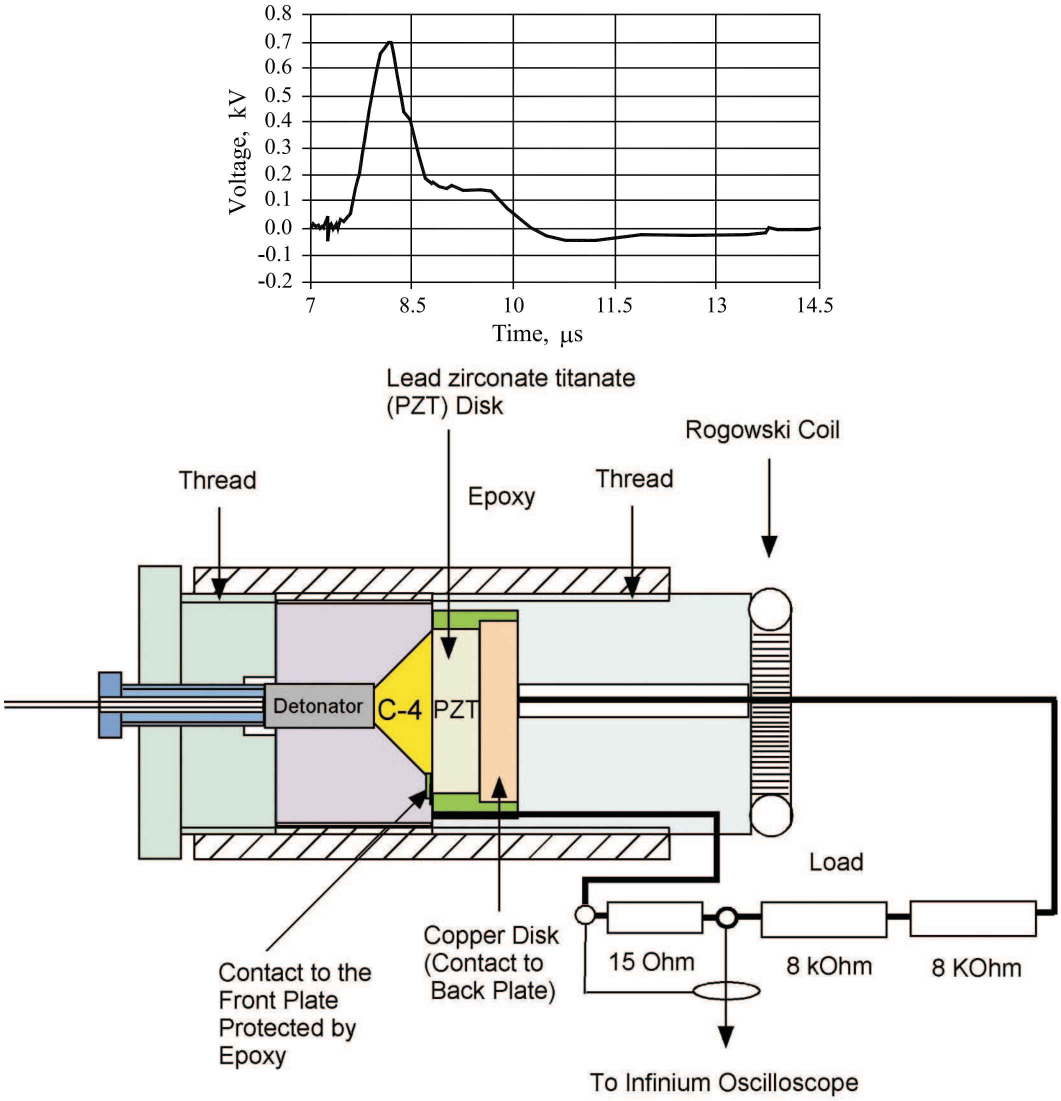

Fig. 12. Schematic diagram (bottom) and representative output voltage waveform (top) of the TTU direct drive ferroelectric generator (courtesy of Texas Tech University).

and piezoelectric materials. Traditionally this has been done with shock waves generated by explosive charges. However, recent work suggests that optimal performance does not occur at shock pressures, but rather at reduced pressures.

Besancon, David, and Vedel [36] in France were probably the first to look at explosive driven FEGs for pulsed power applications. One of the first to recognize that these generators do not operate optimally at shock pressures was Novac et al [37]. They found that damping the shock wave would lead to higher output voltages. Considerable work was done by Prishchepenko in Russia [38]. Fleddermann and Nation [39] have looked at ferroelectric materials for use as cathodes in pulsed power applications.

The work on FEGs was resumed recently at TTU [40] in the U.S. and Diehl in Germany [41,42]. Texas Tech conducted a series of experiments to determine how to optimize their performance. They have worked with both longitudinally (shock wave moves in the same direction as the polarization vector) and transversely (shock wave moves perpendicular to the polarization vector) driven ferroceramic modules and with direct (explosive charge in direct contact with module) (Fig. 12) and flyer plate (Fig. 13) driven ferroceramic modules. The active elements in all the devices were lead zirconium titanate (PZT) disks with diameter $D = 25$ mm and thicknesses of $H = 2.5$ mm and $H = 6$ mm and with PZT cylinders with $D = 21$ mm and $H = 25$ mm. The mass of the explosive charge was varied from 4.2 g to 30 g. Their experimental investigations and numerical studies clearly demonstrate that the output characteristics of the FEG is a very complex balance of what they call "positive" characteristics, like spontaneous polarization of the PZT material and small length and large surface modules, and "negative" characteristics, like diminishing electric breakdown strength (which is

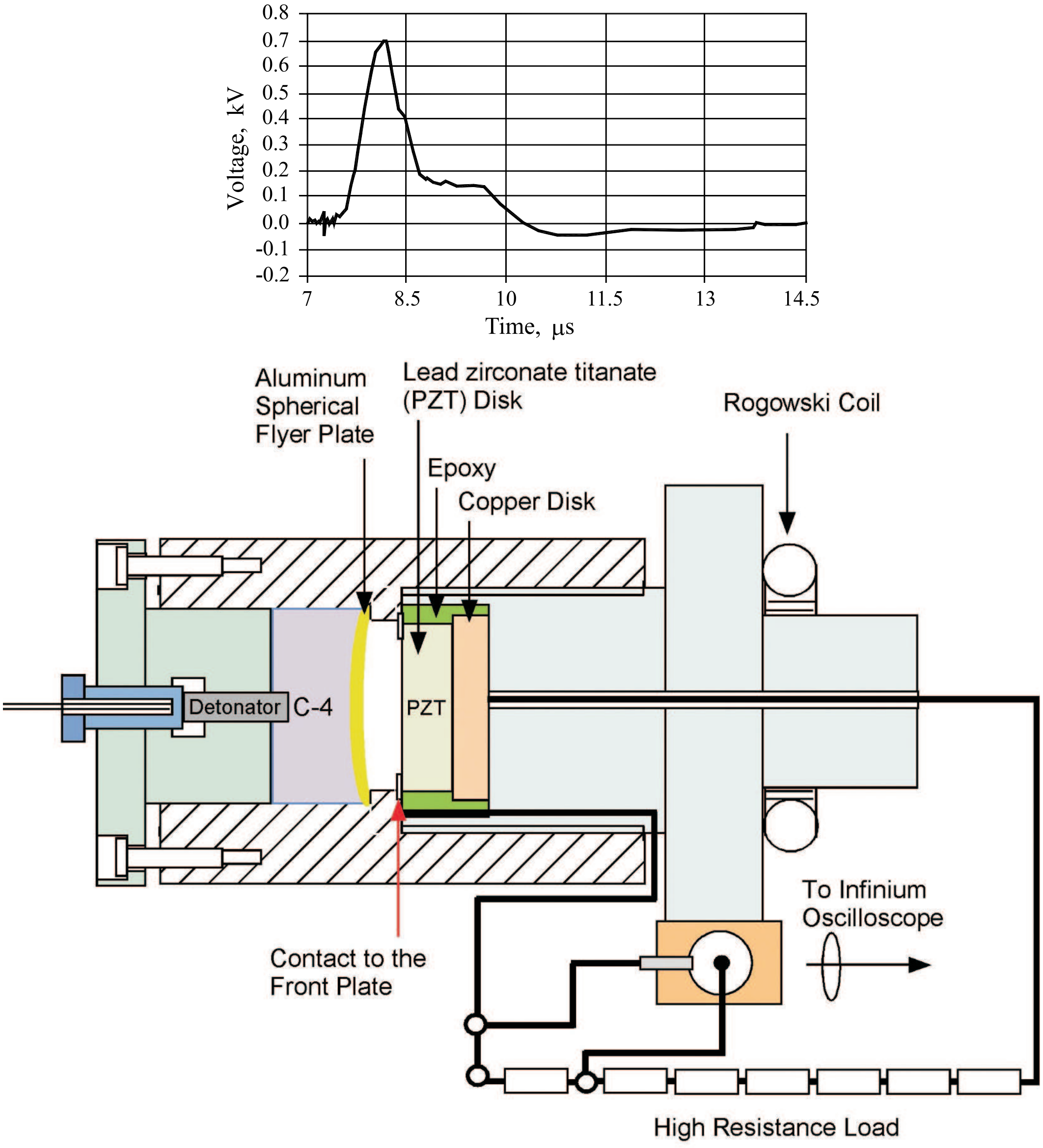

Fig. 13. Schematic diagram (bottom) and representative voltage waveform (top) from the TTU flyer plate version of the ferroelectric generator (courtesy of Texas Tech University).

approximately 3 kV/mm), intensified by diminishing permittivity in the shock-compressed area of the PZT, and bulk leaks, which are believed to become worse as the pressure in the shock wave grows beyond a certain limit. Experiments show that shock-compressed ferroceramic modules can generate pulses with amplitudes up to 9 kV in the resistive part of a load and energies per unit volume of module of 0.1–0.4 J/cm^3. Using a PZT disk with a diameter of 25 mm and height of 2.5 mm, TTU generated 8.8 kV with a FWHM pulse length of 1.5 μs using the flyer plate generator and 8.2 kV with a FWHM pulse length of 0.7 μs when the load was resistance was 14 kΩ and the inductance was 0.06 μH. They generated 21.4 kV with a pulse length of 1.1 μs from a PZT disk with a diameter of 25 mm and height of 6.5 mm when the load was 100 MΩ. They found that the output power decreased as the load resistance increased and as the thickness of the PZT modules increased. They also developed a computer model for the FEG, which was in good agreement with the experimental data.

Diehl [41,42] recently completed a study to determine the optimal pressures for FEG operation and it was found that shock pressures are detrimental, since they cause the ceramics to fracture and can induce electrical breakdown. Their measurements show that simple quasi-static compression of the piezo elements by a 310 mg powder charge is adequate to charge a low-capacitance load to a voltage of about 400 kV with a total energy of approximately 3 J of energy stored in the generator. It was also shown (Fig. 14) that the small fibreglass housings used in

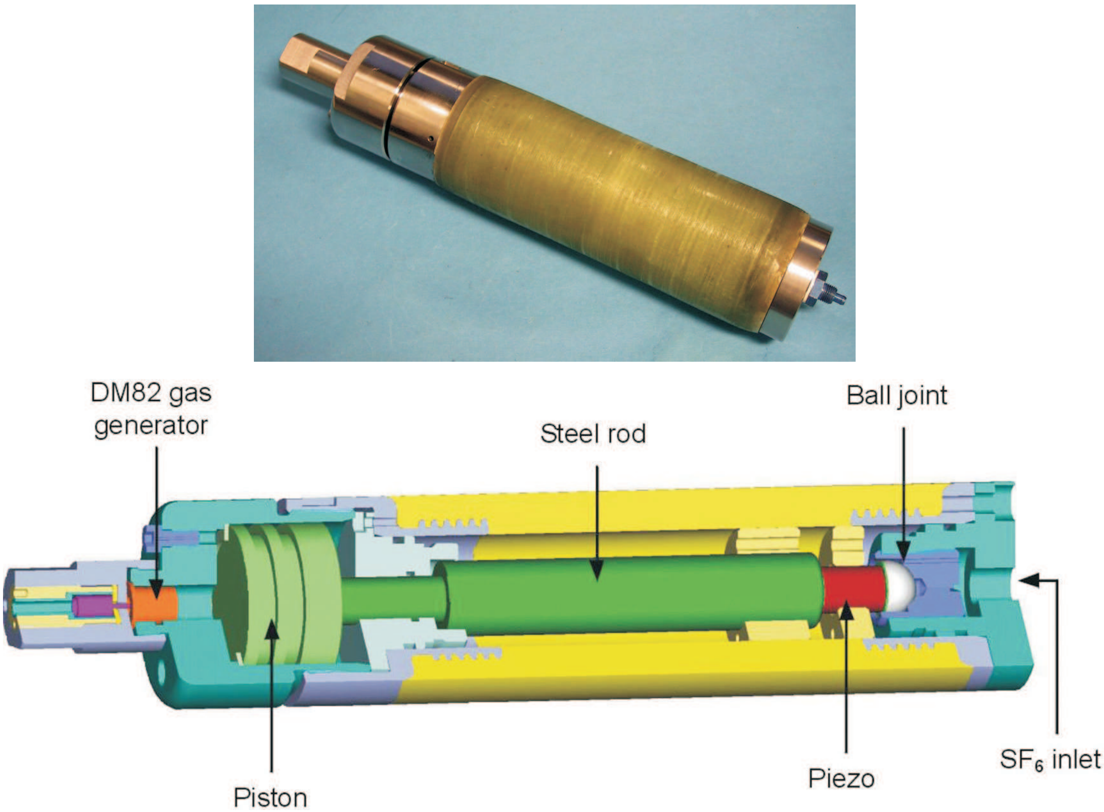

Fig. 14. Photograph (top) and schematic drawing (bottom) of the Diehl FEG (Courtesy of Dieh).

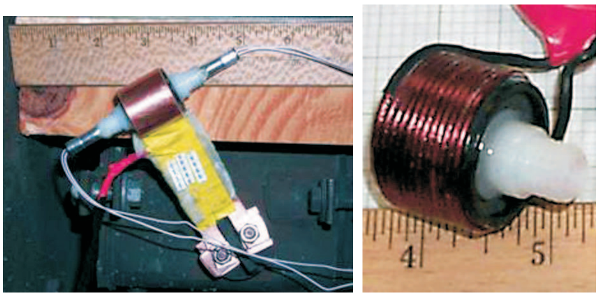

Fig. 15. Photograph of a ferromagnetic generator (top) and its pulse forming coil (bottom).

their tests can withstand the large force required for quasi-static piezo compression. They concluded that, in principle, a voltage as high as 1 MV could be attained in a reasonably compact system and energy as high as 100 J could be attained by cascading up to 100 PZT elements in series and parallel. The volume of the high voltage generator itself would be about 100 mm in diameter and 250 mm long to achieve these specifications. Even higher energy could be attained in a larger system, but the number of PZT elements may become impracticably high.

5. Ferromagnetic Generators

Ferromagnetic generators operation is based on the shock demagnetization of ferromagnetic materials. The simplest version of the FMG is depicted in Fig. 15. When the explosive charge is detonated, a shock wave enters the magnetic material, demagnetizing it and the changing magnetic flux induces a voltage in an output coil.

Work on explosive driven FMGs dates back to the mid 1950s [43,44]. Beginning in the early 1980s, Prishchepenko in Russia conducted extensive testing of FMGs and integrated them with FEGs to produce very compact autonomous power supplies [45]. V.V. Novikov and V.N. Minyeyev [46] investigated the shock loading of ferri- and ferromagnetic materials in 1983. In 1999, A. Prishchepenko and D. Tretyakov [47] investigated both cylindrical and annular versions of the FMG in order to gain an understanding of dissipative losses and to develop a compact source of microwaves. The most recent work has been done by TTU and the Agency for Defense Development (ADD) in South Korea.

Texas Tech [48] used two types of permanent magnets in their experiments: rare-earth NdFeB cylinders (D = 2.5 cm, L = 1.9 cm) and hard ferrite $BaFe_2O_3$ cylinders (D = 2.2 cm, L = 2.5 cm). Two methods were investigated for demagnetizing the magnets. The first is where the explosive charge

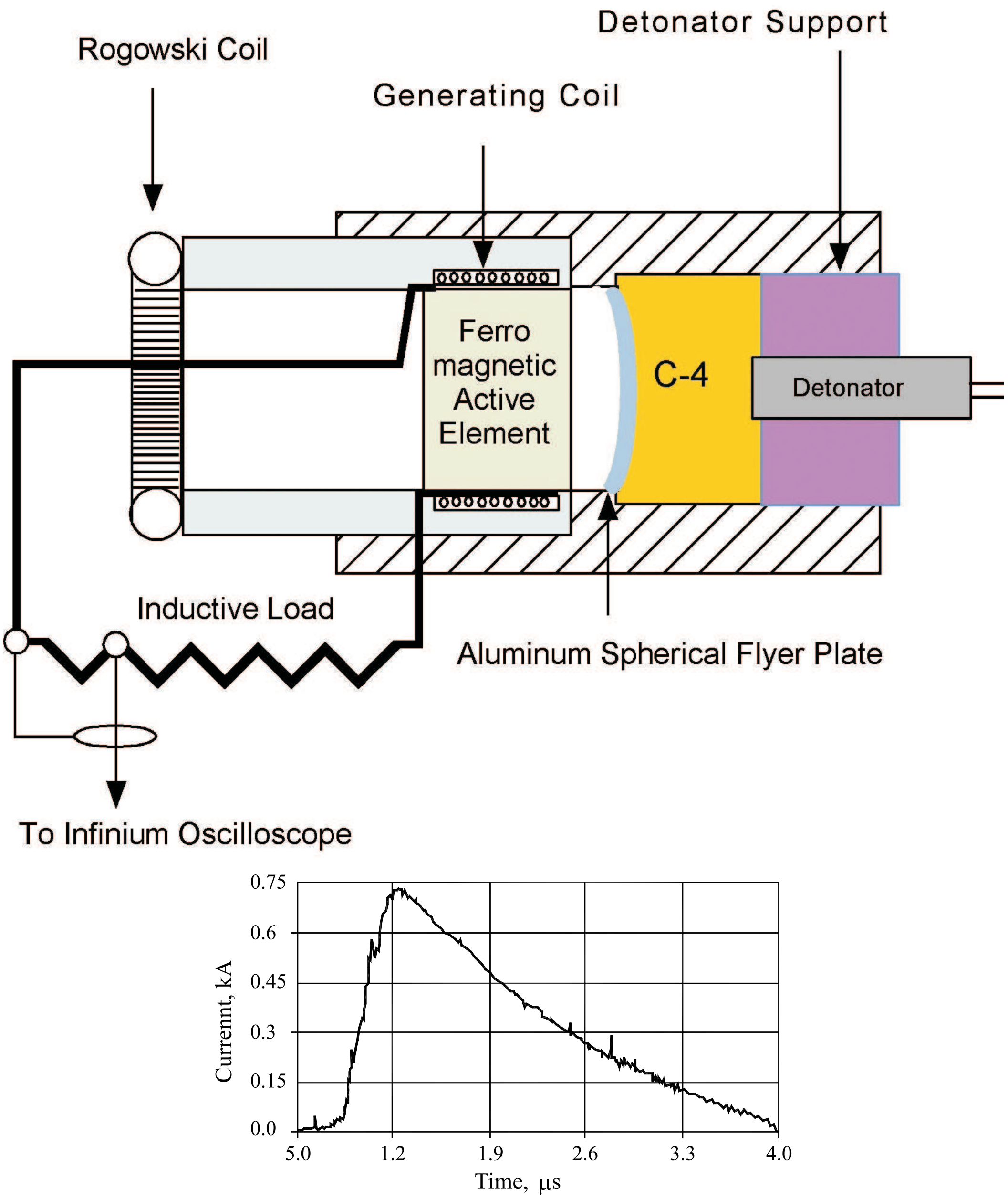

Fig. 16. Schematic diagram (top) and representative output current waveform of the TTU flyer plate version of the ferromagnetic generator (courtesy of Texas Tech University).

was used to drive a flyer plate (Fig. 16) into the magnets and the second is where the explosive charge was placed in direct contact (Fig. 17) with the magnets (both of which are versions of the cylindrical generator). They also investigated a variant of the direct contact generator in which the explosive charge was placed in the center of a hollow cylindrical magnet (annular generator) (Fig. 18). Using $Nd_2Fe_{14}B$ as the working body and 65 g of C-4, their annular generator produced a peak current of 10.3 kA, peak voltage of 47.3 V, 133 kW of electrical power, and a FWHM pulse length of more than 170 μs.

J. Lee, et al [49,50] also investigated the cylindrical and annular versions of the explosively-driven ferromagnetic generators based on NdFeB magnets. They investigated the output characteristics of these generators while varying such design features as length and diameter of the magnets, pitch or number of turns of the generator coils, and the inductance of the load. They performed extensive hydrodynamic simulations of the shock wave propagation in the magnets for both types of generators. Based on both experimental and calculated results, they were able to optimize their design to maximize the energy output. The maximum energy obtained was 0.9 J with an energy conversion efficiency of 6.7 % for the cylindrical generators, having magnets of diameter 50 mm and length 25 mm, and 1.5 J with an efficiency of 9.4 % for the annular

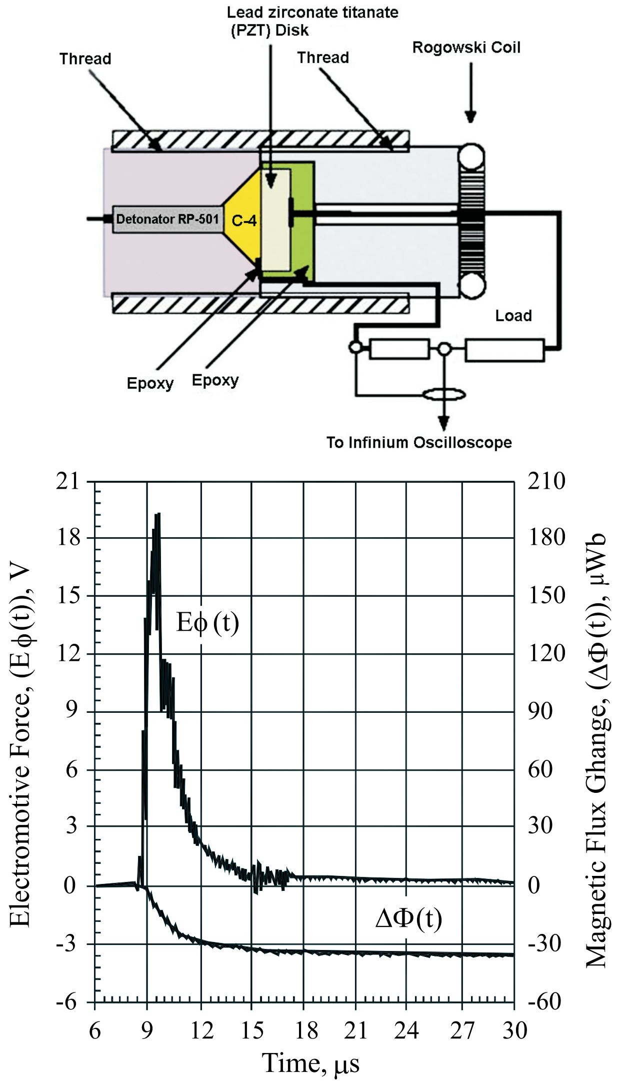

Fig. 17. Schematic diagram (top) and representative wave forms (bottom) for TTU's direct action version of the ferromagnetic generator (Courtesy of Texas Tech University).

generators having magnets of diameter 50 mm and length 40 mm. Based on their studies, they concluded that

1. for the cylindrical FMGs, the ratio of magnet length to diameter has to be kept low, less than 1, to obtain high energy efficiency,
2. annular FMGs show better performance than the cylindrical FMGs; that is, higher energy and efficiency, and
3. annular generators have many advantages over the cylindrical FMG, such as simpler design, smaller size, and no size limitations.

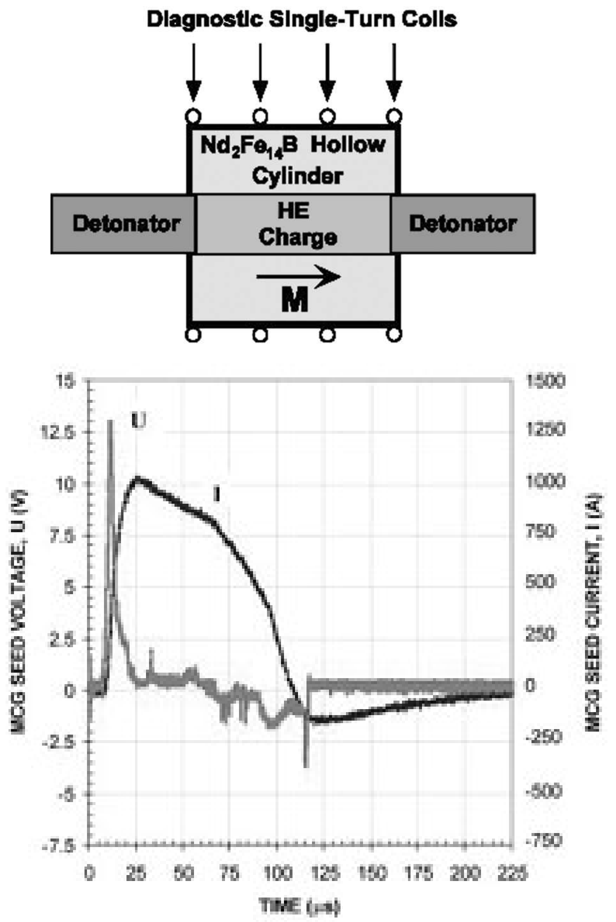

Fig. 18. Schematic diagram (top) and sample of the current and voltage waveforms generated by the annular version of the TTU ferromagnetic generator (courtesy of Texas Tech University).

6. Moving Magnet Generators

Moving Magnet Generators are devices that generate high current and high voltage when ferromagnets are explosively propelled through a coil [51,52]. The changing magnetic flux induces a current in the coil which is delivered to a load, thus converting kinetic energy into electromagnetic energy. The most significant work on this topic appears to have been done by TTU. Initially, TTU used a light gas gun to propel the ferromagnetic projectiles, but then switched to explosives and propellants (Figs. 19 and 20). The projectiles were cylinders made from NdFeB and had a diameter of 2.5 cm and a height of 1.9 cm. The explosive used was C-4 and the propellants used were a smokeless powder and a military propellant. Experiments were conducted with 4 and with 6 pulse generating coils. From their experiments, they reached the following conclusions: it is better to utilize

1. the energy of the gases formed by the detonation of the explosive rather than the energy of the

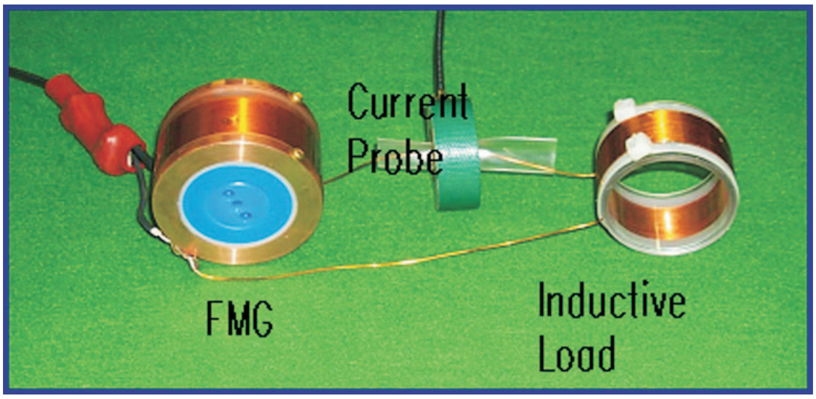

Fig. 19. Ferromagnetic generator (courtesy of the Agency for Defense Development, South Korea).

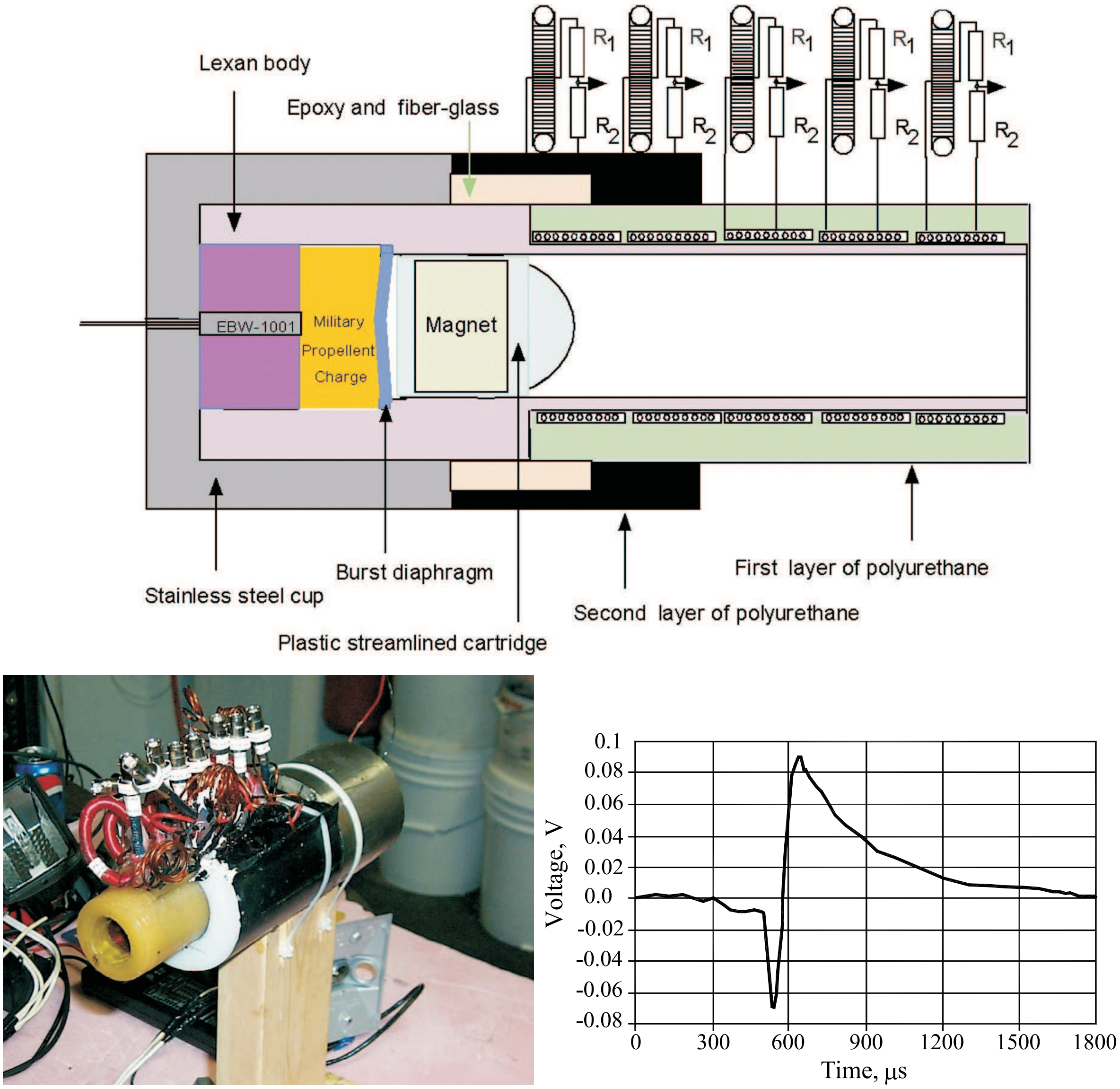

Fig. 20. Schematic drawing (top), photograph (middle), and representative waveform(bottom) from the fourth output coil of the TTU moving magnet generator (courtesy of Texas Tech University).

flyer plate accelerated by the detonation and

2. the military propellant rather than the C-4 is the better accelerant, since it has a higher burn

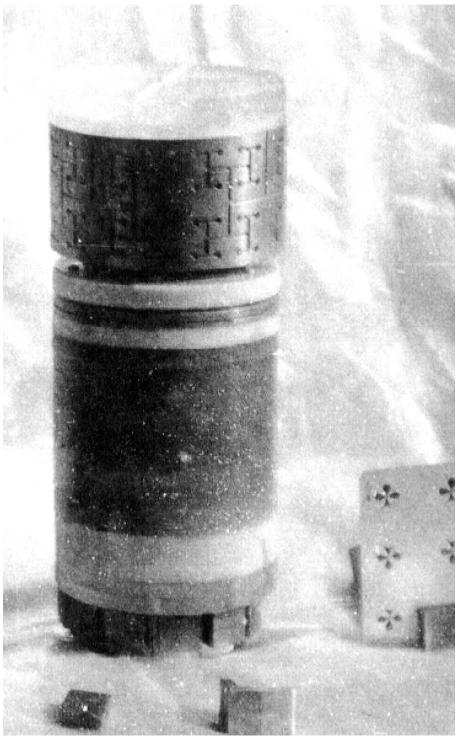

Fig. 21. Cylindrical shock wave source (courtesy of A.B. Prishchepenko).

velocity and the gases have a higher energy.

In addition, by using the propellant, the device is not self-destructive, which means the generator can be reused and its preserved integrity means that all the gas energy can be used to accelerate the projectile. They also showed that the current pulses from the pulse generating coils can be used separately creating multiple pulses or combined to generate one large pulse and that if the projectile velocity reaches 200–300 m/s, kiloamp pulses are possible. They found that the power in the load is directly proportional to the projectile velocity and that a reduction in the number of turns in the pulse generating coils leads to an increase in the current and power in the load [52].

7. Shock wave (Semiconductor) Generators

When certain dielectrics, such as silicon, germanium, gray tin, silicon oxide, cesium iodide, germanium iodide, and oxidized aluminum powder, are subjected to high pressures, they transition from an insulating state to a conducting state [53]. Whereas most MCGs have metal armatures, the SWG uses this insulator-to-metal transition as the armature to compress the magnetic field. By far, the most significant work on these devices was done by A.B. Prishchepenko in Russia. He developed, built, and tested both cylindrical (Fig. 21) and spherical (Fig. 22) versions of these generators [50].

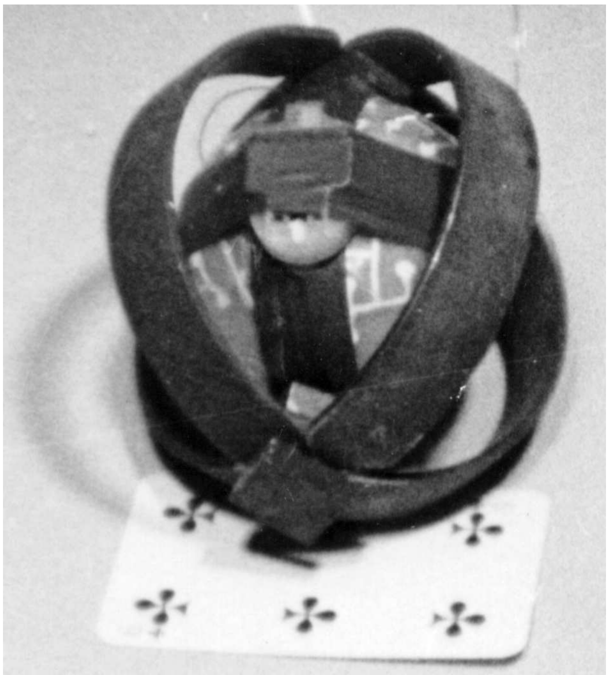

Fig. 22. Spherical shock wave source (courtesy of A.B. Prishchepenko).

Recently, researchers at Loughborough University in the UK reported on a study of the insulator-to-metal transition in aluminum powder [3]. Under normal conditions, very pure aluminum powder is a relative good insulator due to the formation of a thin oxide coating on the particles. When this coating is destroyed by shock loading, the aluminum powder transitions from a good insulator into a good conductor. Loughborough has concluded that the mechanism responsible for destroying the insulting coating is a fast, low pressure, elastic precursor moving ahead of the main high pressure shock wave front. They found that the shock precursor in air is essential for efficient operation of a powder cascade, since under reduced atmospheric conditions the flux compression experiments were less efficient.

8. Superconducting Generators

Superconducting generators operate on the basis of a phase change; that is,, the transition from a superconducting state to a non-superconducting state. This phase change can be induced by a number of means including the use of explosives. The most notable work has been done by A.B. Prishchepenko [54], who has worked for a number of years to develop compact autonomous microwave sources.

The SuG (Fig. 23) [54] consists of a feed coil

Fig. 23. Superconducting generator (Courtesy of A.B. Prishchepenko).

(1) made of copper and (2) sapphire ring, which are both submerged in liquid nitrogen (3). A fast rising current pulse initially creates a magnetic field in the gap between the coil and ring. The inductance of the coil at this moment is very low (because of the presence of the superconducting ring) and the current rises rapidly together with the magnetic moment of the current in the superconducting ring. However, at some moment in time, the feed current and external magnetic field reaches a critical value and a phase change occurs, which moves from the outer diameter of the ring towards its axis. The velocity of this process, which depends weakly on the external magnetic field, is rather high; i.e., on the order of kilometers/second. It is important to note that a significant amount of energy is to be delivered to the switch in a fraction of a microsecond, since this is how long it takes for the phase transition to propagate to the center of the ring. When the phase transition front reaches the inner edge of the ring, the magnetic moment of the ring's electrical current sharply changes and microwaves are emitted. The radiated power is proportional to the second derivative of the magnetic moment [54].

9. Power Conditioning

Many applications require stored energy or energy from MCGs require that the energy be delivered in times on the order of microseconds, but these stores deliver the energy in hundreds of microseconds. One way to accomplish this is to use opening switches, but these switches can consume up to 50 % of the energy from the power supply.

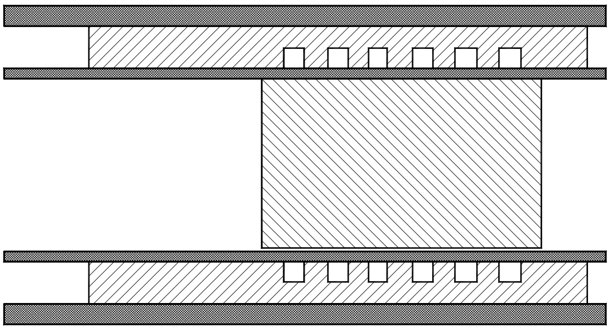

Fig. 24. Explosively Formed Fuse: A – outer conductor, B – inner conductor, C – grooved Teflon insulator, D – explosive initiated simultaneously on axis.

Explosive driven generators typically require a power conditioning circuit to enable their use with a variety of loads. There have been some advances in power conditioning components such as switches, transformers, and nonlinear modulator circuits. These power conditioning circuits perform several functions including impedance matching, pulse sharpening, and voltage up-conversion. For example, high power microwave sources, such as the VIRCATOR or MILO require voltages of 400–500 kV, but MCGs can only deliver a voltage of 100–150 kV. One way to achieve these voltages from an MCG is to use a combination of switches and transformers.

In 1998, J.H. Degnan et al [55] proposed using the explosive formed fuse (EFF) opening switch with output closing switches to deliver a fast rising, several hundred kilovolt pulse with a nearly flat top pulse for ~ 1 μs from an inductive store to a high impedance load. Goforth et al [56] proposed using the EFF with MCGs in which multimegampere currents need to be diverted to low impedance loads or interrupted to produce high voltages across high impedance loads.

Explosive formed fuses have conducting elements that are deformed by an explosive charge against a dielectric die (Fig. 24). This changes the fuse geometry, so that the conducting element cross section decreases and the ratio of the current conduction time to current interruption time is higher than for standard fuses. This enables more control over when the current interruption occurs. Los Alamos [57] reports that they have used the EFF to interrupt currents ranging from 19 to 25 MA into low impedance loads and 10 to 20 MA into dynamic loads. They have investigated EFF switches with lengths ranging from 43 to 100 cm for generating high voltages (300 to 500 kV) in high impedance loads. Los Alamos [58] has done some small scale testing with currents of 0.5 MA into a conductor of width 6.4 cm. A plane-wave detonation system was used to drive the EFF.

Another method for up-converting the voltage from explosive power supplies is to use a transformer. Typically air-core transformers have been used, but when the voltages go above 500 kV the transformer has to be immersed in oil to prevent electrical breakdown. However, this approach adds weight and complexity to the system. To overcome these limitations, Loughborough University has proposed two innovative transformer designs: magnetically self-insulated transformers and air-core autotransformers.

Magnetic insulation is a proven technology that has been used in high voltage devices such as transmission lines, plasma opening switches, and MILOs. The basic premise of magnetic insulation is that magnetic fields can be used to prevent electrical breakdown by diverting the electron flow generated by high electric fields. Magnetic self-insulation is where the self-insulating magnetic field is generated by the device to be protected own electric current. The Loughborough design is based on one first proposed by Winterberg in 1970 [59]. The primary winding of this transformer was a single-turn coil of copper sheet surrounding an evacuated glass tube and the secondary is either a helical wire-wound single-layer coil or spiral-wound strip of metallic foil inside the tube. Loughborough built a small prototype in which the primary was a single turn with a diameter of 40 mm and a length of 63 mm and the secondary consisted of 35 turns with a diameter of 17 mm and pitch of 1.8 mm. Proof-of-principle experiments confirmed that magnetic insulation was demonstrated at voltages up to 100 kV.

In some cases, loads require high current, but lower voltages. Loughborough has developed a matching or interfacing air-core transformer (which they called an autotransformer) designed to deliver 1 and 2 MA to a load [60]. The autotransformer had three primary turns wound from wide copper sheet, with the middle also acting as the secondary winding. To prevent deformation of the conductors due to high magnetic pressure, the conductors were thick and clamped. They demonstrated that this relatively simple, easy to build, lightweight, and inexpensive transformer was capable of delivering 1.1 MA.

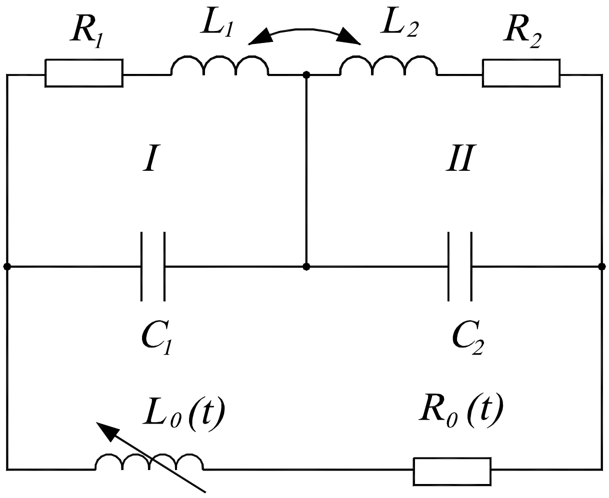

Fig. 26. Simplified equivalent circuit of the MCG output current modulator, based on two nonlinearly coupled circuits: $L_0(t)$ – MCG inductance, changing with time; $R_0(t)$ – MCG resistance changing with time; L_1,C_1, and R_1 – inductance, capacitance, and resistance of the 1st modulator circuit; L_2,C_2, and R_2 – inductance, capacitance and resistance of the second modulator circuit.

One of the problems associated with explosive pulsed power devices are that they are single shot devices. Loughborough [61] developed a technique for producing twin high voltage pulses in series from a single shot device. This multiple-pulse, twin-output, high-voltage generator (Fig. 25) consists of a single power source and an array of parallel-connected exploding fuses, with compact transformers to enable achieving the required output voltages. They conducted more than 30 shots with their prototype generator and were able to generate 150 kV pulses on two loads with impedances ranging from 50 to 100 Ω.

Another problem associated with explosive pulsed power devices is efficiently transferring the energy from the pulsed power device to its load at frequencies of interest. It has recently been suggested [62] that a nonlinear two tank circuit could be used to achieve these goals. Analysis indicates that the use of a coupled system of two nonlinear tuned circuits (Fig. 26); i.e., low-frequency and high-frequency circuits, as the load for the MCG, can lead to a broad spectrum of current oscillations that will broaden

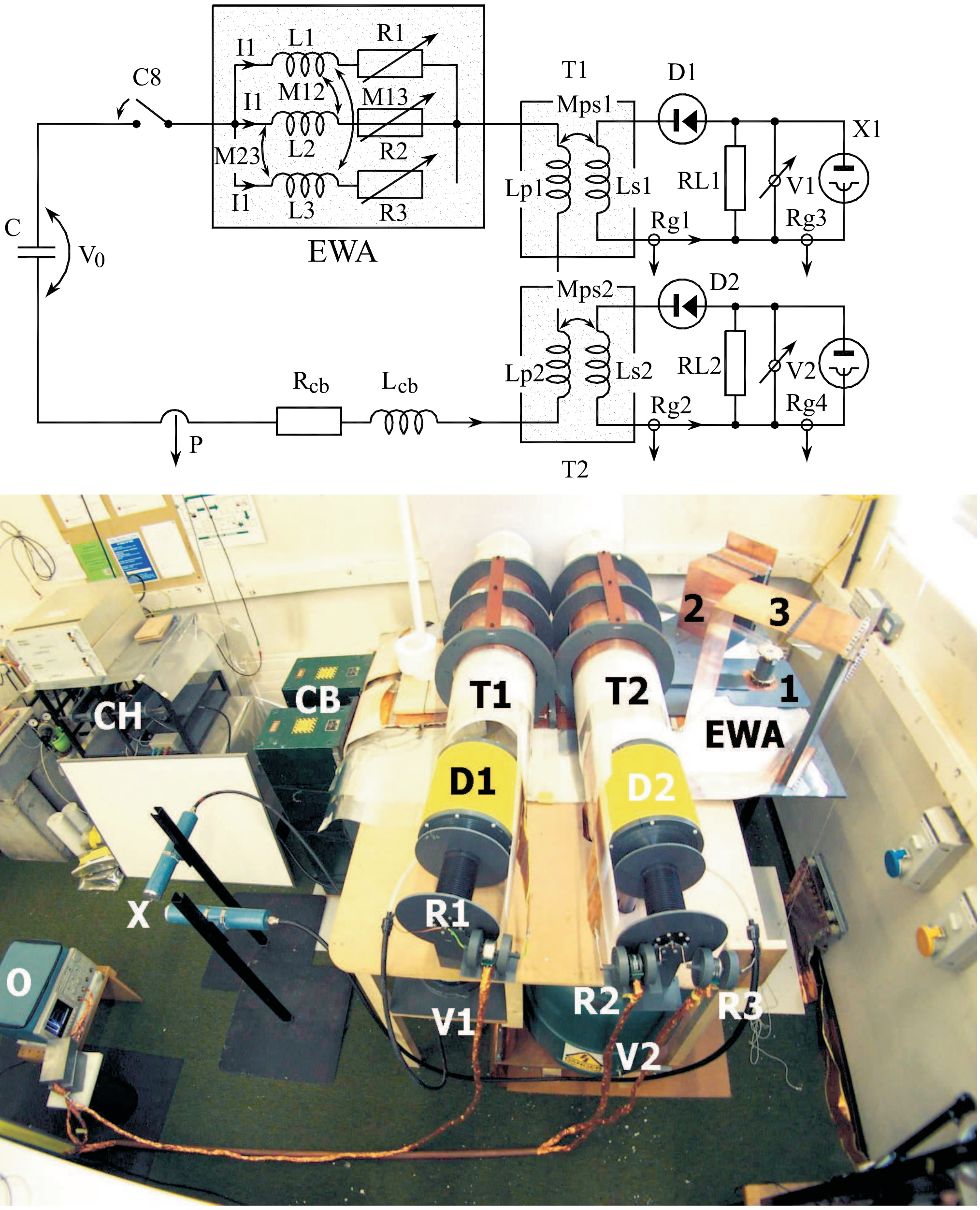

Fig. 25. Electrical equivalent scheme (top) for the Loughborough Multiple Pulse, high-energy system and photograph (bottom) of the complete system (CH-HV charger, CB-capacitor bank, T-transformers, D-diodes, R-Rogowsky coils, V-voltage sensors, A-attenuators, O-oscilloscope, X-X-ray sources).

the radiated spectrum of the signal into a higher frequency regime (< 1 GHz). Calculations indicate that the proposed two tank circuit driven by an MCG effectively generates broadband microwave signals at powers on the order of 7–20 MW in the frequency band 200–900 MHz, when operating into loads up to 10 Ohms. In order to verify the numerical results, an MCG simulator and a two tank circuit were constructed and are shown in Fig. 27.

10. Explosive Pulse Power Applications

The MCG has been used to drive a number of loads including high power lasers, high power microwave sources, railguns, plasma focus machines, z-pinch devices, and so on. In recent times, there major focus has been on using them to drive high power microwave sources and direct drive devices. The latter are ultra wideband systems in which a MCG is used to directly drive an antenna through a power conditioning circuit. These are very compact autonomous radio frequency sources. Many of these earlier efforts are summarized

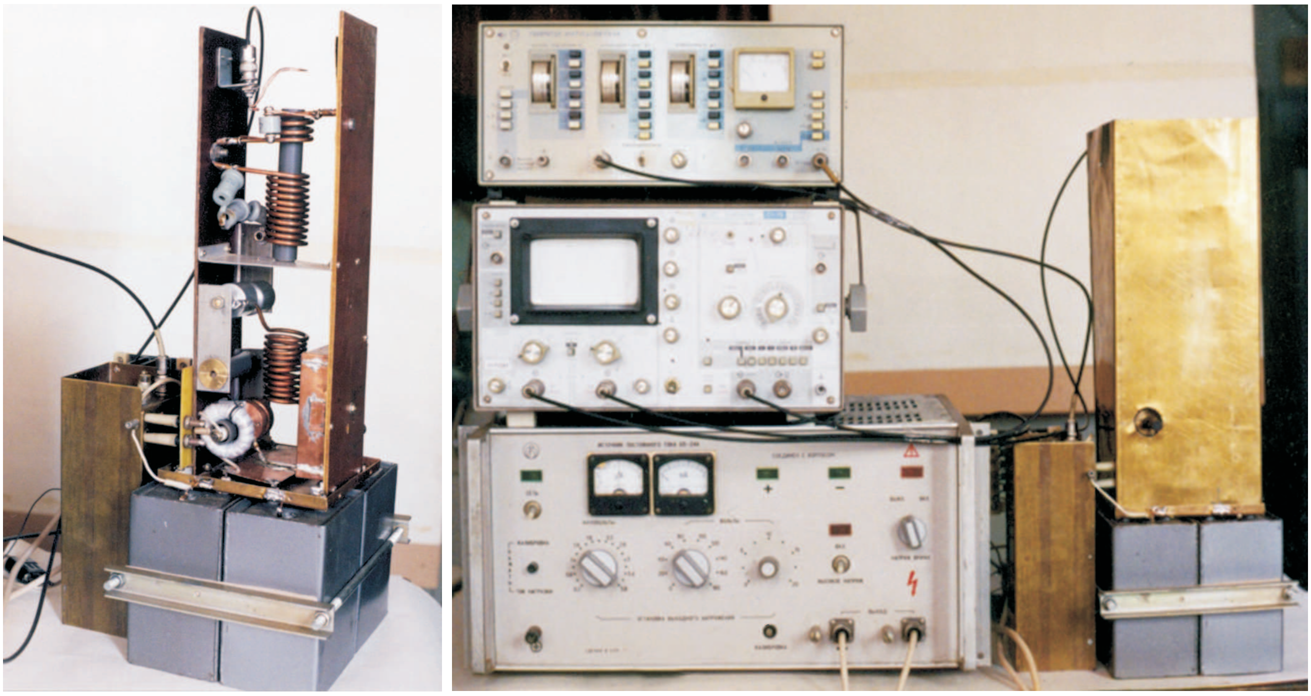

Fig. 27. Photograph of the experimental stand used to study the two-tank circuit.

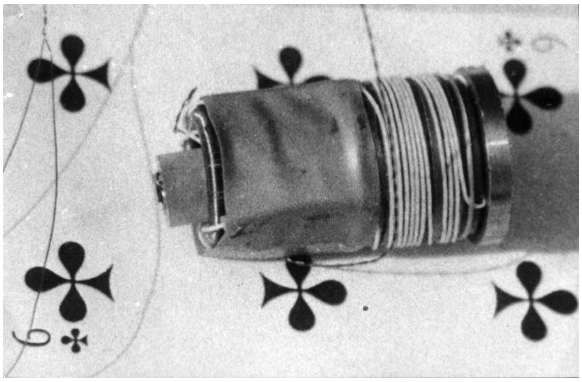

Fig. 28. Combined generator of frequency (courtesy of A.B. Prishchepenko).

in the monogram Magnetocumulative Generators [2] and the review paper by Fowler and Altgilbers [7]. The most recent activity has been to used explosive power supplies to seed larger explosive power supplies in order to develop completely autonomous power supplies; that is, power supplies that do not require a prime energy supply such as a capacitor bank or batteries.

While the FMG and FEG have been considered as the power supplies for direct drive devices, current interest has been to use them, along with the EMHDG, as seed sources for MCGs. Prishchepenko has used a FMG to drive a FEG (Fig. 28) [63], Texas Tech has considered the FEG as a seed source and has used a FMG to seed a MCG (Fig. 29) [64], and V.A. Demidov et al [65] used a FEG to power two helical MCGs, where the two MCGs were connected to each other by a step-up transformer.

The TTU autonomous explosive pulsed power system [64] consisted of a FMG as the source of prime energy and a mini-spiral MCG. The annular FMG had an outer diameter of 2.54 cm, inner diameter of 0.76 cm, and a length of 1.9 cm. The 1 g explosive charge in the FMG was initiated with two detonators at both ends of the generator. The mini-MCG had a coil inner diameter of 2.2 cm and a length of 2.3 cm. The aluminum liner had an inner diameter of 0.76 cm and an outer diameter of 0.95 cm and was loaded with C-4. The load of the combined FMG-MCG systems was a copper wire with diameter 0.16 cm and length of 70 cm. The peak current from this combined system was 396 A, peak voltage was 14.7 V, and peak power was 5.26 kW. The current gain was 1.8, voltage gain 10.5, and power gain 3.0. It was noted by TTU, that this autonomous system does not require switches, energy stores, converters, or nonlinear elements such as diodes and transistors.

Demidov et al [65] used a FEG to seed two helical MCGs in series. The PEG used piezoceramics at the working medium. The first MCG in the cascade had a helical coil with diameter of 50 mm and length of 400 mm. The total length of the generator was 540 mm and it contained $\sim$ 200 g of high explosive. This first generator was connected to the second generator through a matching transformer. The primary consisted of two turns of copper wire with a diameter of 0.2 mm and had an inner diameter of 100 mm. The secondary consisted of 80 turns of

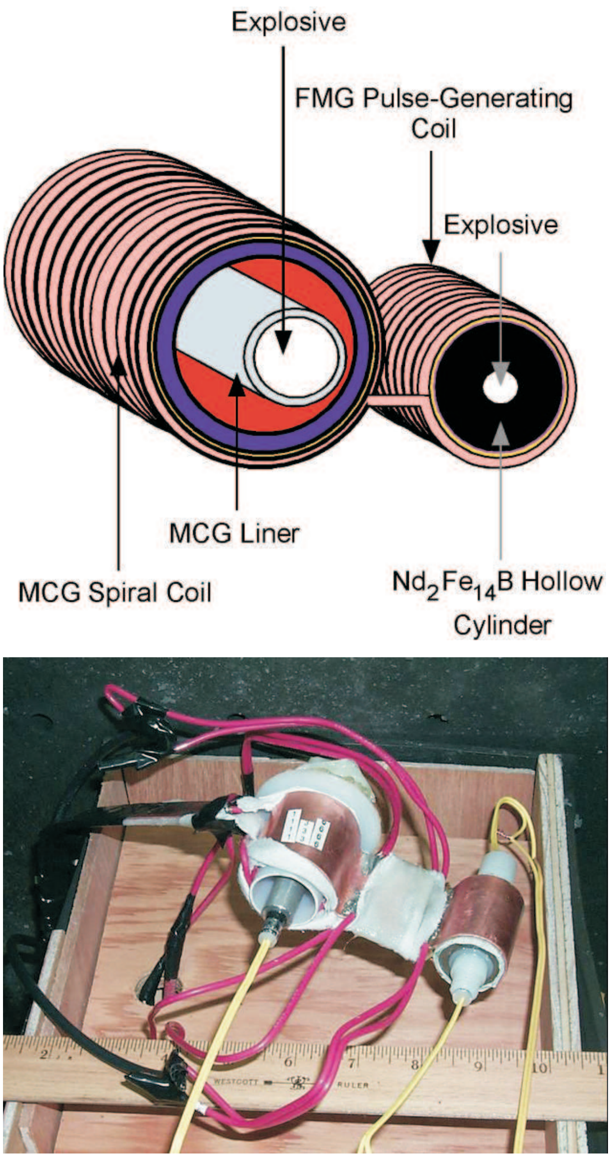

Fig. 29. Schematic diagram (top) and photograph (bottom) of Texas Tech autonomous explosive pulsed power system (courtesy of Texas Tech University).

1.8 mm diameter wire and had an inner diameter of 96 mm. The inductance of the primary was 244 nH, the secondary was 430 μH, and the mutual inductance was 9.9 μH. The second helical MCG consisted of a helical coil with an inner diameter of 100 mm and length of 700 mm. The explosive charge had a mass of 1.7 kg. The FEG delivered 6 J of energy to the first MCG, the first MCG delivered 1.5 kJ to the primary of the transformer, and the transformer delivered 1.0 kJ to the second MCG. The second MCG delivered 410 kJ to a 30 nH load. The energy gain of the system was 68,000 and the total time of operation was 150 μs.

11. Summary

Even though the roots of explosive pulsed power can be traced back to the mid 1950s and early 1960s, we continue to learn about their capabilities and their limitations. Over the years, interest in these devices has been cyclic and we appear to be on one of the many upswings in their development with organizations in many countries now working on them. One of the major achievements has been the introduction of completely autonomous explosive pulsed power systems. The replacement of bulky and heavy capacitive stores with ultra compact explosive driven seed sources has made the use of MCGs more practical. Of course, the development of improved compact FMGs, FEGs, and EMHDGs have opened the door for their use in a variety of applications.

Texas Tech [66], Texas A&M, and Loughborough University [67] have developed, built, and tested relative simple, reliable, and repeatable helical MCGs capable of generating hundreds of kiloamps to megamps of current. Texas Tech and ADD have continued to improve the performance of the FMG and TTU and Diehl have been able to generate relative high voltages (~ 400 kV in the case of Diehl) with their FEG. Many of these devices have been integrated with one generator serving as the seed source for other generator versions. Advances have been made in power conditioning such as compact high voltage transformers, EFF switches, and modulator circuits. These recent advances have led to the development of autonomous explosive driven power sources.

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