# AN ECONOMICAL, 2 STAGE FLUX COMPRESSION GENERATOR SYSTEM

R.E. REINOVSKY, and P.S. LEVI
Plasma Physics Branch
Air Force Weapons Laboratory
Kirtland AFB, New Mexico 87117

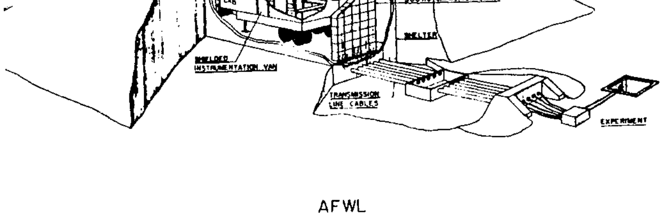
J.M. WELBY
Maxwell Laboratories Inc.
Albuquerque, New Mexico 87117

## ABSTRACT

A two stage Magneto-Cumulative Generator employing simple construction techniques and inexpensive explosives has been explored by the Air Force Weapons Laboratory. The first stage in the cascade MCG system is constructed with a helically wound, insulated cable stator and an aluminum armature filled with (Comp C-4) explosive. The 0.5 - 1 MJ output energy of this generator is coupled, inductively, to the second helical stage via a single turn aluminum coil. The 12 microhenry second stage helical stator is wound with progressively increasing diameters of insulated cable that increases the pitch and thereby decreases the generator inductance gradient toward the output. The cascade system is expected to multiply a 250 KA, 150 KJ initial charge to an approximately five Megamp, five Megajoule output delivered to a 400 nanohenry coaxial load.

## INTRODUCTION

Explosive driven magnetic flux compression devices, or magneto-cumulative generators (MCG's) have been explored for at least 20 years as sources of very large electrical currents and very high magnetic fields (1,2,3,4,5,6). Generators have produced current outputs from 10's of KA to 10's of MA (5,7) and output energies above 10 MJ. They represent relatively simple and compact energy sources and, despite their non-reusability, represent economical systems for some applications. At the AFWL, generators have been introduced as energy sources which provide an alternative to large, high performance capacitor banks for physics experiments which require very large electrical energies but which may not require the very high powers available from such banks or for experiments which can be successfully conducted in the simplier surroundings of an open range. Experiments at the AFWL are conducted in a relatively simple experimental area, as shown in the drawing in Figure 1, which includes an explosive hardened shelter rated for explosive charges from 500-1000 lb, containing shielded enclosures for electrical instrumentation and high speed photography and a 300 microfarad capacitor bank rated at 60 KV for providing initial loading for the generators.



AFWL
EXPLOSIVE PULSE POWER
TEST SITE

FIGURE 1 *Experimental Location*

Of the wide variety of generator configurations that have been described in the literature, the helical generator represents one configuration capable of both relatively high output currents, and relatively high energy gain -- at the expense of relatively long output pulse time. While such slow operation could represent a severe limitation on the feasibility of driving certain types of experiments with helical generators, the successful demonstration of multi-megajoule pulse compression techniques for single pulse, multi-megamp systems (8) has resulted in renewed interest in the relatively efficient helical configuration. In this paper, we discuss a family of helical generators for which simplicity, flexibility, reliability and economy rather than novelty of configuration were the primary considerations in their design.

## GENERATOR DESCRIPTION

A family of generators comprised of two members of essentially common design and distinguished by size have been designed, constructed and operated. The smaller generator is approximately 18 cm diameter and 40 cm long and is designed to produce 0.5-1 MJ output while the larger member is about 35 cm diameter and 80 cm long. The small generator, as shown in the drawing in Figure 2, consists of a helical stator (stationary coil) wound, on a removable form, from a number of parallel, stranded, commercial insulated copper wires secured to terminal rings on each end and encased in an outer jacket of fiberglass and epoxy. The terminal rings are square in cross section, and are machined from flat stock and provided with a hole pattern suitable for terminating 1,2,3,4 or 6 parallel conductors. Stranded copper conductor ranging in size from AWG #4 to #1/0 are terminated with commercial wire lugs which are crimped (or brazed) to the conductor and bolted to the rings. Stranded conductors were chosen for ease of winding the small diameter helix and the use of crimp connection permit easy termination of the conductors during assembly. While the use of both stranded conductors and crimped connections were matters of initial concern, neither has yet been observed to limit the performance of the generators. The outer insulating fiberglass shell, which takes most of the "hoop" stress during initial generator loading and generator operation, and which maintains the generator's mechanical integrity during handling and assembly, is a fiberglass cloth which is impregnated with an air curing epoxy. This product is sold commercially for medical use in making casts (to immobilize injured limbs!) and which may soon be available in non-sterile form for industrial applications. The simplicity of the total generator concept of a custom wound stator of adjustable length and pitch and rapid curing epoxies makes it possible

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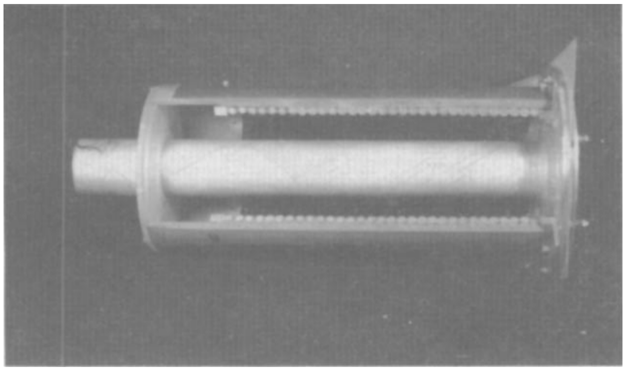

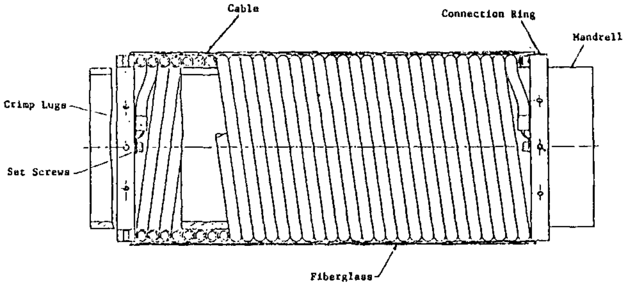

FIGURE 2 *Construction Of Small Generator*

to assemble the stator of a one megajoule class generator, with inductances ranging from 1 to 50 microhenries, in a fraction of a work-day.

The inner, cylindrical armature of the small generator is stock 3 inch aluminum tubing, alloy 6061, purchased in the hard (T6) condition, machined on the outside to remove imperfections, and (usually) machined or honed on the inner surface to provide uniform wall thickness. To maximize on the concepts of economy and flexibility, several high explosive systems were explored which avoided the need for expensive, machined HE charges. Several commercial gel explosive systems which could be custom poured into armatures by (qualified) field personell were tested for detonation velocity, energy yield, uniformity, and overall performance. Figure 3 shows a high speed photograph of a 44 cm long copper armature driven by one such gel system. The interframe time is 3.0 microseconds. The armature surface is covered with a checkerboard decal to aid in analysis of the photograph (but which does inhibit diagnosis of the formation of surface cracks). The photo clearly shows smooth, uniform expansion of the armature to more than twice its initial diameter as the expansion cone moves from left to right. A variety of such experiments were conducted with with both aluminum and copper armatures with M/C ratios (ratios of metal mass to explosive mass) ranging from about 1 to 3. Analysis of the photographic data showed a consistant cone velocity of 5.5 - 5.7 mm/uSec (which is 10% faster than the commercially advertised 5.0 mm/uSec for the unconfined gel in 3" sections). For these charge to mass ratios (1 to 3), the cone angles ranged from 11 to 6 degrees which corresponded consistantly to "Gurney" velocities of about 2 mm/uSec and which leads to a yield estimate of between .5 and .6 Kcal/gram. By comparison with conventional PBX systems, with velocities of 7-8 mm/us and yields .8 - 1.0 Kcal/gram, the gel system's somewhat slower velocity is balanced by its lower yield and results in armature motion comparable to that previously reported for PBX systems. In addition to gel explosive systems, field assembled granular explosive systems (composition C-4) were also tested and produced armature motion data comparable to Figure 3, but with predictably higher burn velocities, almost 8 mm/uSec and cone angles of 14-16 degrees. Armature performance such as that shown in Figure 3 is hardly unusual, but the fact that such nominal performance free from jets, geometrical aberations or variance in velocity were obtained with the simplest of explosive systems is worthy of note. This result suggests that simple systems can take their place beside the machined PBX systems and the low energy liquid (nitromethyne) systems traditionally used in helical generators.

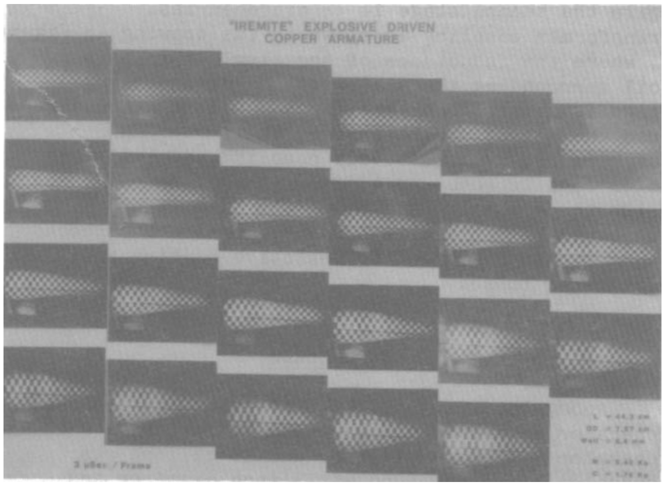

FIGURE 3 *Explosively Driven Aramature Expansion*

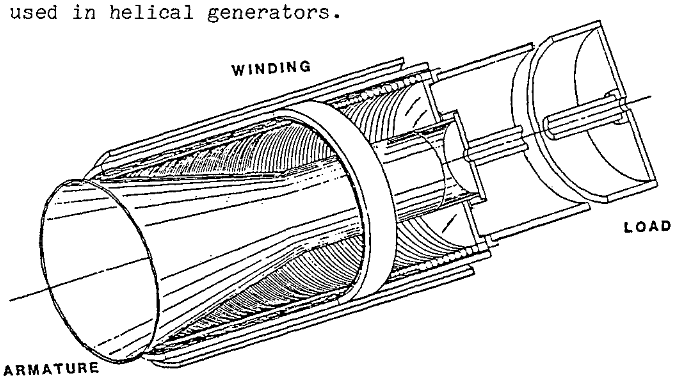

*Figure 4 Large, Multi-pitch Generator*

The larger of the generators is similiar in design to the smaller generator. As shown in Figure 4, however, the large generator is wound with variable pitch -- steeper at the crowbar (initation) end; and shallower at the output (load) end -- to shape the dL/dt of the generator in order reduce the rate of flux compression and hence the voltage near the output end where the currents become very high. The approach taken to achieve pitch changes is that of changing conductor sizes. Near the crowbar end, the helical stator is wound from 12 parallel, #10 copper conductors, after about 6.2 turns each #10 conductor is connected with a simple crimp connection to a #4 copper conductor (by removing the center of the larger bundle inserting the smaller wire into the larger one and crimping a simple sleeve around the connection). The twelve #4 conductors are wound for another 1.5 turns and then each is connected to a #1-0 copper conductor in the same manner. The twelve large conductors are then wound for about 1 turn and terminated on a terminal ring, for a total inductance of approximately 12 microhenries. The entire winding is encased in an outer sleeve of epoxy and commercial PVC pipe. The armature consists of a stock 6 inch aluminum (or copper) tube machined on the inner and outer surfaces to remove imperfections and driven with explosive systems comparable to those described for the small generator.

## ELEMENTARY MODELING

The most elementary of geometric/circuit models were applied to evaluate performance of various helical generator designs. As shown in Figure 5, the operaton of the generator was described by calculating the time changing inductance of the generator from the geometry of a cone advancing into the cylindrical volume defined by the helix of the stator. Three distinct regions are identified: I) the entry of the cone into the cylindrical volume; II) the progress of the cone down the volume;and III) the exit of the cone at the load end. In each region the volume occupied by the field due to current in the helix is calculated, and from that volume the time changing inductance of the generator is found. No attempt is made to account for the azimuthal component of the field due to current flow in the armature or to calculate the field density precisely in various parts of the winding.

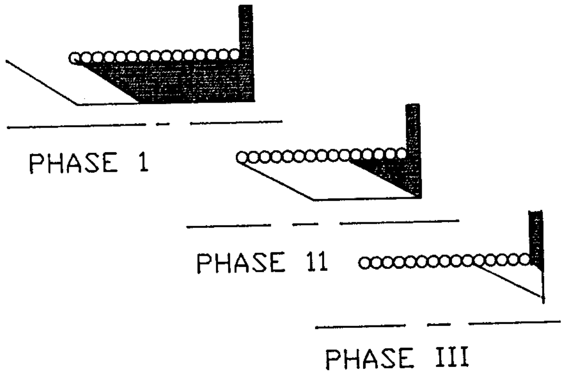

FIGURE 5 *Elementary Geometric Modeling*

The time changing inductance of the generator is then incorporated into a finite difference circuit calculation including both the initial loading loop and the output loop to the load. Resistive losses in the generator run are identified through both a time varing component of resistance (intended to account for flux diffusion losses), and a time independent component of resistance which may be identified with "contact resistance" of the armature/ helix contact (probably made somewhat worse by the presence of the undistrubed insulation on the winding wires). Figure 6 shows an example of the calculated performance of a generator consisting of 14 turns of 2 parallel conductors for different load inductances in which the losses are dominated by a 10 milliohm time independent contact resistance. The modeling assumes that the generator inductance runs to zero (no breakdown at the output) and shows the familiar result that at low values of load inductance, the losses reduce the output current faster than the additional flux multiplication can increase it leading to net reduction in energy multiplication. The optimum inductance for the generator of this description is about 150 nH.

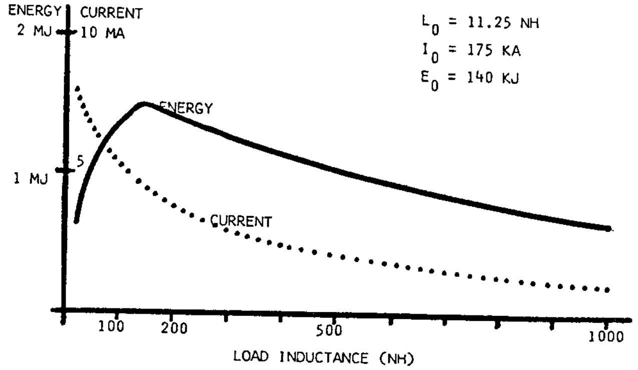

FIGURE 6 *Modeling Results using Fixed Losses*

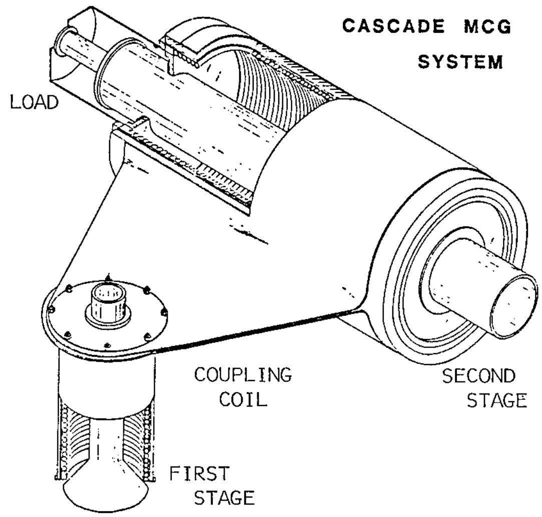

FIGURE 7 *Two Stage Cascade System, Inductively Coupled*

## CASCADE SYSTEM

Figure 6 suggests a range of 5-10 in energy gain as a reasonable expectation for systems of this type, with energy gains of 12 as perhaps the upper limit. While the tailored inductance of the large generator may be expected to enable operation at higher final currents and energy multiplications, it is apparent that to obtain multi-megajoule output energies from large generators significant fractions of a megajoule initial loading is required. While direct loading from capacitor banks can be considered, the attractive features of generators (their small size, and economy) soon become outweighed by the cost and complexity of the large loading source! One, hardly origional, approach to this delema is to use the output of one generator to seed another (7). The obvious difficulty is, of course, the need to match the initial inductance of the second generator stage (perhaps several to several 10's of microhenries) to the inductance (perhaps several hundred nanohenries) which takes best advantage of the first stage. For the two generators described, the first small generator is best suited to operate into a load of 100 to 200 nH while the second stage is 12 microhenries. Transformer coupling as shown in the drawing in Figure 7, where the inductance of the single turn primary coil surrounding the stator of the second (large) stage is about 250 nH provides an acceptable way to load the second generator from the first. Furthermore, by inductively coupling the two stages, no current is required to flow in the second stage prior to crowbar -- and hence the load is not subjected to early time current, nor are the second stage windings subject to resistive heating and associated losses.

## PERFORMANCE

Among the tests of the performance of the small generator an experiment in which a 7.5 turn 4 wire generator, 18 cm in diameter and 40 cm,long was conducted. The armature was 3 inch diameter and driven by the granular ( Composition C-4) explosive system. The generator was directly loaded to about

250 KA from a capacitor bank operated at 30 KV. The relatively high voltage loading represents a departure from previous work and permits significantly reduced loading time, and presumable somewhat reduced loading losses. Thus the initial loading energy was about 100 KJ into the 3 microhenry initial inductance. The configuration of the loading circuit however, did not require seed current to flow in the load -- which is an advantage for some loads which are initially an open circuit. The current measured in the 135 nH load is shown in Figure 8. The peak current of about 2.5 MA results in about 0.5 MJ energy in the load for a multiplication of about 5 in energy and 10 in current. For comparison the results of the elementary model for the 7.5 turn generator is plotted in Figure 8 as well. Fixed resistive losses of 2.5 milliohms are included in the calculation and the correspondence between this experiment and model for the basis for our selection of 5-10 milliohms as a reasonable value for other model calcualtions.

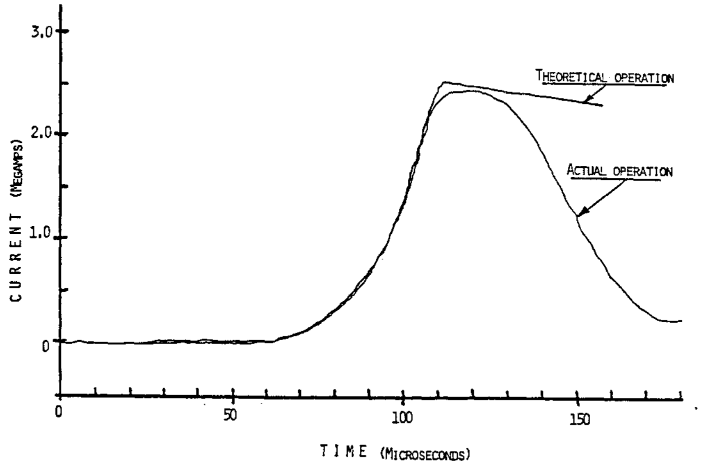

FIGURE 8 *Comparison of Predicted and Operational Performance of Small Generator*

In addition to the evaluation of the small generator performance, the large generator has been operated at very low loading to obtain initial estimates of performance with results that are in reasonable agreement with predictions. And an inductively coupled pair of small generators have been tested to confirm the coupling technique proposed in Figure 7 for coupling between large and small generators.

## CONCLUSIONS

A family of helical generators has been designed with primary attention focused on simplicity and economy of both construction and operation. Major mechanical short-cuts and the verification of very simple explosive systems have brought the per unit price for material, explosive and labor to well below $1,000 for generators which have demonstrated 0.5 - 1 MJ outputs. Even at this price generators are not competitive with large banks for lengthy investigations requiring many experiments. They are however a highly adaptable power source that can perform a wide variety of one-of-a-kind experiments more economically and probably more quickly than a large bank can be reconfigured for the purpose. In that role, such generators represent a very useful complement to existing large banks for enhancing experimental capability.

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