INVITED

PULSE POWER APPLICATIONS OF FLUX COMPRESSION GENERATORS*

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Characteristics are presented for two different types of explosive driven flux compression generators and a megavolt pulse transformer. Status reports are given for rail gun and plasma focus programs for which the generators serve as power sources.

Introduction

The first explosive driven flux compression generators were described over twenty years ago. Since that time a great deal of work has been published, and many different kinds of generators have been described. Much attention has been devoted to theoretical aspects of generator performance, and various applications have been discussed.

Most of the work reported to date has been restricted to rather specific topics. Some more general treatments are available, however. The first major conference devoted to the subject was held in 1965 at the Frascati Euratom Laboratory. The general status of the field to this time is surveyed fairly well in the proceedings of this conference[1]. Other more general treatments, each including some updating of the field, were given by Herlach[2] in 1968, Knoepfel[3] in 1970, and Fowler, Caird and Garn[4] in 1975. The second international conference featuring this field was held in Washington, DC in 1979. The proceedings[5] of this conference contains the most recent collection of papers dealing with flux compression. It includes a series of papers by Pavlovskii and his associates[6] that treats the helical class of generators in great detail.

In the following sections we discuss two different classes of generators presently used in Los Alamos programs referred to as strip and plate generators, respectively. The description and performance of a generator powered megavolt pulse transformer is also included in this section. Status reports of programs in which the generators are used are given in the next two sections. First described is a rail gun program done jointly with the Lawrence Livermore National Laboratory (LLNL), in which power is supplied by strip generators. This is followed by a description of a program in which a plasma focus is powered by plate generators.

Generators and Pulse Transformers

Strip Generators

The strip generator shown in Fig. 1 is the cheapest and simplest generator used at Los Alamos. Its most useful characteristic is its capacity to carry relatively high currents (up to megamperes peak values) for long times (up to nearly a millisecond). Initial inductances vary considerably with the particular dimensions selected but are typically in the low microhenry range. Although one of the earliest generator types developed[7] some detailed construction features have been furnished only

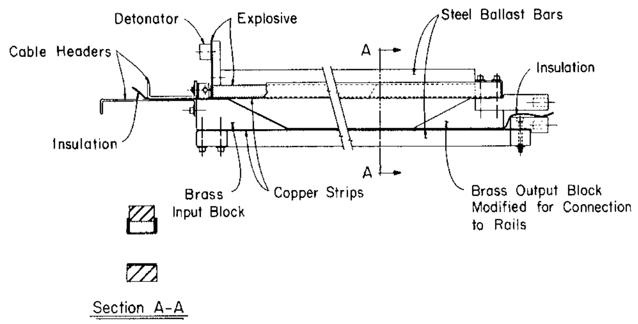

Fig. 1. Conventional strip generator. Sectional view AA shows locations of explosive and ballast bars.

recently after it proved to be a useful power source for railguns.[8]

The generator consists of long parallel strips of copper, one of which is overlaid with explosive sheets, together with input and output blocks for capacitor bank cable input leads and for connections to the load respectively. The copper strips are about 57 mm wide, 1.6 mm thick, and 2.45 m long, and are separated by 51 mm. The long edges of the upper copper strip are bent up to add structural rigidity. This strip then assumes the form of a shallow U-shaped channel as noted by the sectional sketch of Fig. 1. Two layers of C-8 Detasheet explosive, 45 mm wide, are placed over the upper copper strip. To minimize expansion of generator components from magnetic forces steel ballast bars, 51 mm wide and 12.7 to 25 mm thick, are laid on top of the Detasheet explosive and directly under the bottom copper strip. The input and output wedges are cut from 51 mm square brass bar stock, and then drilled and tapped individually to accommodate cable input header attachments and to make output connections to the various loads tested.

Initial flux is supplied to the generators by a large capacitor bank located at the firing site. The detonator is fired after maximum current is introduced into the generator and load. The resultant detonation of the explosive strips first results in closing the current input slot, thus trapping the magnetic flux. As detonation proceeds the top plate is driven into the bottom plate, thereby pushing the flux into the load.

These generators can be altered easily to meet varying conditions:

- Pulse lengths can be changed by lengthening or shortening the copper strips.
- Inductance can be changed by changing the spacing between strips.

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- The widths of the generator strips, explosive, and ballast can be increased when larger currents are required.

- Some independent control on the time variation of inductance can be achieved by varying the separation and widths of the copper strips along the length of the generator.

As pointed out previously[8] one of the major problems encountered with these generators is the control of undesirable component displacements from magnetic forces. This has been accomplished fairly well to date by use of ballast bars, as shown in Fig. 1, and by widening the generator components. Use of various clamping arrangements is another possibility. While all of these methods are effective, they get increasingly cumbersome as current levels increase and pulse times are lengthened.

As an alternative way to control these expansions, we have started development of "inside out" strip generators similar to those reported by Herlach, Knoepfel and Luppi[9]. A schematic of this generator is shown in Fig. 2. The magnetic stresses are disposed more favorably for this class of generator since they tend to push the lighter, explosive driven plates inwards. On the other hand the outer plates can be quite massive and, further, they are also subject to simple clamping arrangements.

Some of these generators have been test fired into static loads at current levels higher than those of our conventional strip generators. Steel bar ballasting was placed over the outer plates. Flash x-ray pictures, shown reproduced in Fig. 3, were taken in the vicinity of the generator output-load connections. The upper photograph shows the shot setup, while the lower photograph was taken about 10 μs before generator burnout. As seen from this photograph, the ballasting on the outer plates held the system together quite well. The short top and bottom plate sections angling into the generator output connections were not ballasted on this shot. Their large displcements are apparent upon comparing the two photographs. The photographs reveal another interesting phenomenon. The remaining undetonated region of the armature has been compressed considerably, as seen from the lower photograph.

Plate Generators

The plate generator, with parallel plates, is illustrated in Fig. 4. Simple forms of this generator were used many years ago but its development into the relatively sophisticated devices now used can be found in papers by Caird et al.[10,11]

Current is supplied through the input slot to provide initial flux to the load and generator. The explosive pads are initiated simultaneously over their surfaces, closing the input slot and driving the top and bottom plates together. The flux is then

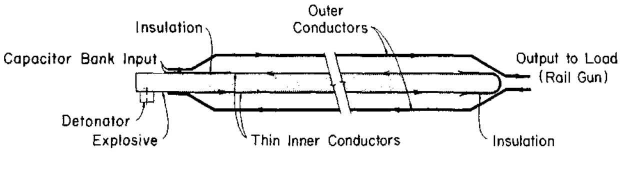

Fig. 2. Inside out strip generator schematic.

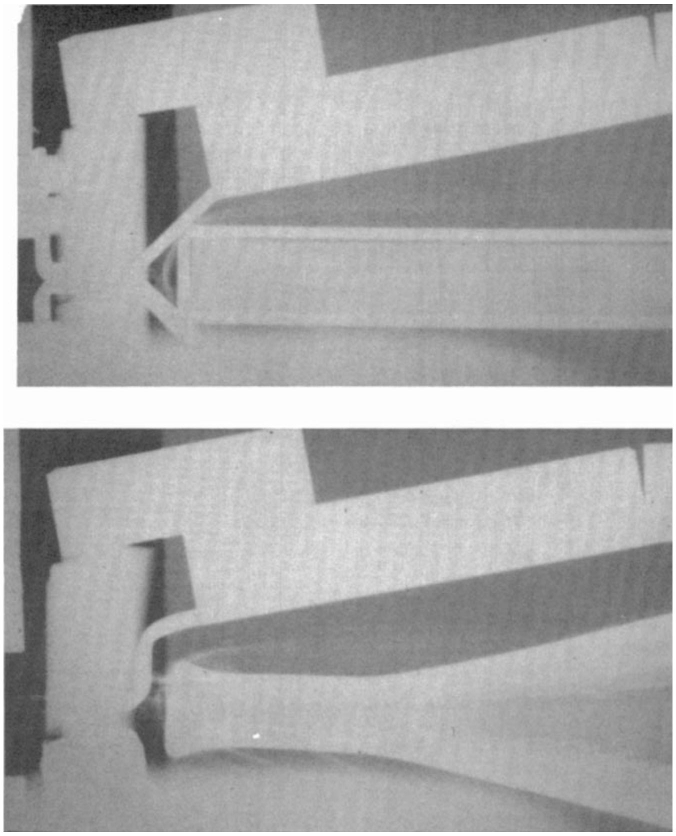

Fig. 3. Flash x-radiographs of an inside out strip generator test. The upper figure shows the setup in the vicinity of the generator output to the load (at the left). The lower photograph, taken 10 μs before generator burnout, shows displacement of several generator components from magnetic forces.

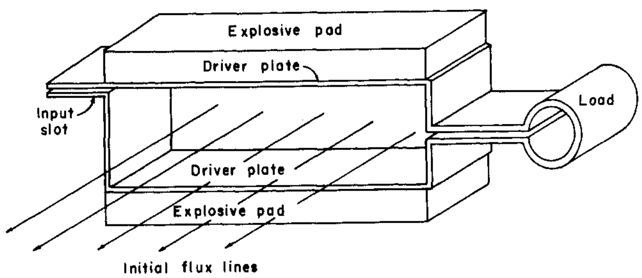

Fig. 4. Sketch of plate generator connected through a transmission line to a cylindrical load coil.

concentrated into a region of lower inductance, thus increasing the system's magnetic energy.

These systems have several features particularly valuable for powering low, but increasing, inductance loads, such as typical Z-pinch devices. Amoung these are:

- high current carrying capacity (in excess of a megampere per cm of plate width near burnout);

- speed: total burntimes depend upon the top and bottom plate separations, other parameters being fixed. In some models used, generation times are as short as 5 μs. Additionally, current rise times near burnout can exceed 10^{12} amps/sec per cm of plate width;

- large $\dot{L}$: this parameter, the time rate of change of the generator inductance, is one of the factors controlling a generator's ability to drive current into a load. Unlike most of our generators, the parallel plate generator maintains relatively large $\dot{L}$'s at peak current. This has proved to be of considerable importance for powering loads whose inductance increases with time;

- uncomplicated geometry variations: the generator length, width and plate separation are, within limits, easily varied, thus allowing changes in current carrying capacity, initial inductance and generation time.

We describe one more variation possible with this generator that has proved particularly effective in some applications.[11] This variation is to shorten the driver plate separation at the input end. With this configuration the driver plates are no longer parallel. These generators are called trapezoidal after the shape of their cross-sections, as opposed to the rectangular cross-sections of the standard, parallel plate generators. The total generation time is still determined by the longer plate separation at the output end of the generator but the rate of change of the generator inductance can be substantially altered. This can significantly affect various circuit parameters such as the voltage developed across a load. Calculated voltages developed across a 30 nH load are plotted vs time on Fig. 5 for several generator configurations, in which the only parameter changed is the plate separation at the generator input. For all cases the generator plates are 510 mm long and 150 mm wide, separated by 127 mm at the generator output end. The initial generator current is 1 MA. The highest voltages developed occur at generator burnout for the parallel plate configuration (127 mm curve), but are substantially lower at intermediate generation times than those of some of the other configurations. In some applications, for example the plasma focus described later, current pulses should be only a few microseconds long, initial voltages across the focus breech should be several tens of kilovolts, and preferably not get significantly higher during the plasma rundown phase.

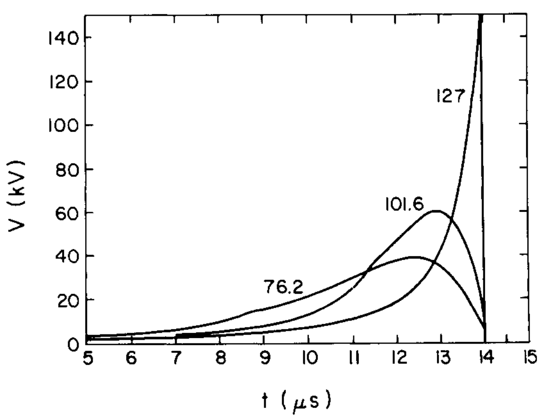

Fig. 5. Calculated voltages vs time produced by plate generators across a 30 nH load. The curves are identified by the generator input plate separation, in mm. All other generator parameters, including the output plate separation of 127 mm, were fixed.

Our method for meeting these conditions is to switch the plasma focus device in parallel with the 30 nH load a few microseconds before generator burnout. Use of the 101.6 mm trapezoid generator would develop 30 kV across the breech for a 3 μs focus rundown time, as opposed to only about 10 kV if the parallel (127 mm) generator were used.

The curves of Fig. 5 would no longer apply after paralleling the plasma focus load into the circuit. However, more detailed analysis shows that voltages developed across the plasma focus breech after switching remain substantially lower than those that would be developed by the parallel plate configuration.

Impedance Matching Megavolt Pulse Transformers

As a rule, flux compression generators are low impedance devices. As direct power sources, they are well suited for correspondingly low impedance loads. However, their performance as direct power sources continuously degrades with increasing load impedance. Using a compact step-up transformer, we have used plate generators as prime power sources to produce fast rising, high voltage pulses across high impedance resistive loads in the 10-100 Ω range.

The pulse transformers employed in these experiments were similar to the metal tape wound, high voltage, step-up autotransformer of Martin and Smith[12,13]. Such transformers are attractive for certain applications because of their simplicity, ease of construction, and low cost. These qualities are especially desirable when the device is to be used on a single shot basis. The transformer of Martin and Smith consists of a tape winding, with turns overwound and separated by sheet insulation. In one version, the input voltage is applied across the outer turn. The output is taken across the entire winding with the high potential appearing on the inner turn. The most unusual feature of the design, permitting operation in the megavolt regime, is immersion of the entire transformer winding in a slightly conducting dielectric liquid (e.g. weak $CuSO_4$ solution). Thin paper wicks are wound next to the metal tape to soak up the solution, assuring penetration between each turn of the winding. The solution, everywhere in contact with the transformer windings, tends to smooth out the potential gradients at the edges of the metal, thus preventing edge breakdown and flashover.

Our pulse transformer differs from the conventional design as the secondary coil was separately fabricated, encapsulated in a thin-walled vacuum-tight container, and impregnated with dielectric liquid. It was then inserted into a bored block that served as the single turn primary of the transformer. The coil block was connected directly to the generator via a short flat plate transmission line.

The secondary coils for our experiment were hand wound from annealed 0.05-mm copper foil. Paper wicks of identical thickness were wound flanking either side of the foil. The width of the foil was not tapered as is sometimes done in the Martin design. Turn-to-turn insulation was provided by several sheets of Mylar with adjoining sheets separated by a 0.008-mm layer of Kraft tissue. The secondary coil, once wound, was placed in the lucite housing. Connections were brought out to one end of the housing from the low potential outer turn and the high potential inner turn. The housing was then sealed and evacuated. Distilled water was successfully used as the vacuum impregnated, dielectric grading fluid. Upon insertion of the secondary into the primary coil, an external connection was used to join the outer secondary turn to the coil block. This type of assembly was done at the expense of a few percent loss in the coupling coefficient. It did, however, allow for much simplified fabrication. This was important as each transformer was used for one shot only. This type of assembly also eliminated the difficulty in trying to make low-inductance and well-insulated tab connections to the primary coil. After assembly completion, the entire transformer was placed in an oil bath.

The circuit employed in these experiments is shown in Fig. 6. A two-sided plate generator L_G was constructed such that the output section containing the transformer was insulated from the generator during the time in which the initial flux was introduced and during the early action of the generator. The generator current during this early time was carried by the ballast or shunt loops L_B. The first motion of the driver plates served to self switch the transformer and load R_L into the circuit in parallel with the ballast load.

The capability of this pulse forming system is exemplified by an experiment which employed a 25.5 Ω load. The generator was designed with a slight trapezoidal aspect and a 6.3-cm mean plate separation. The distance between input and output slide planes in the generator was 52.3 cm. The driver plates were made from 3.2 mm thick aluminum alloy sheet. The initial inductance of the generator was 170 nH with a total design compression time of 7.7 μs. The primary coil L_p was 27 nH with a 10.3-cm diameter and a 34.3-cm width. The secondary coil had 31 turns of 30.5-cm wide copper foil. Coil turns were separated by 0.2 mm of Mylar insulation. The inductance of the secondary coil was 19 μH based on inner and outer diameters of 7.6 and 9.6 cm respectively. The coupling coefficent K for the pulse transformer was 0.79.

The voltage pulse produced across the 25.5 Ω load is shown in Fig. 7. The pulse was measured using a two-stage resistive divider network (10^4:1). This device was a simplified version of that described by Pellinen and coworkers[14]. The first stage was a 0.5 m long $CuSO_4$ solution divider with a 100:1 division. The load voltage in this experiment peaked at about 1.1 MV. Total energy delivered to the resistive load was about 40 kJ.

The pulse in Fig. 7 exhibits a 10-90% risetime of 3.7 μs after a 7.7 μs generator run. Other risetime criteria show the voltage pulse to be rather fast at late time. For example, the e-folding time to peak is 1.0 μs, and the time needed to double the voltage to peak is 0.6 μs. Because a convenient, self activated

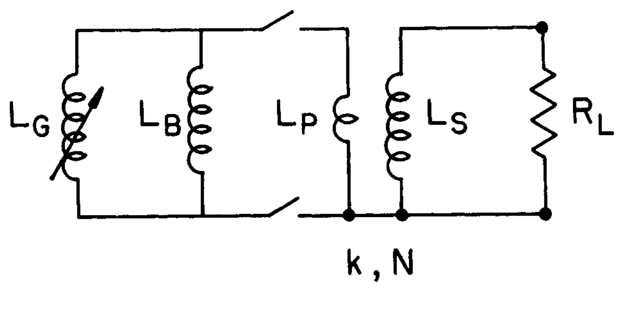

Fig. 6. Circuit schematic for a plate generator used to power a resistive load through a high voltage transformer.

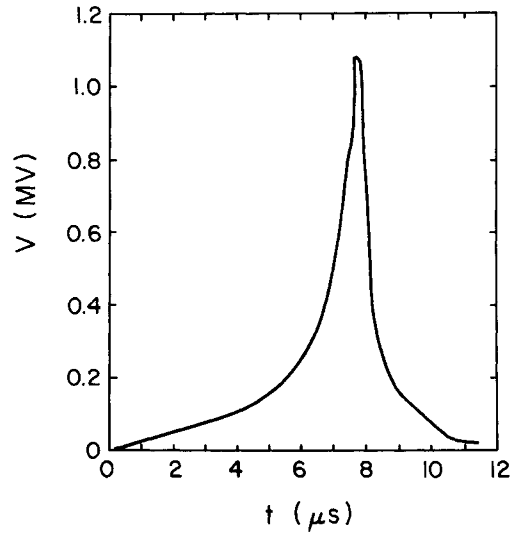

Fig. 7. Voltage signal developed across a 25.5 Ω load transformer coupled to a plate generator.

closing switch technique was used in this experiment, the early rise of the pulse is arbitrarily long. Simple closing switch schemes can be used to engage the transformer and load at times later in the generator compression and shape this pulse to a 10-90% risetime of 1 μs without serious degradation in peak voltage and delivered energy.

The dimensions of the transformers described here are characterized by small diameters and small diameter-to-width ratios. This design provided a compact transformer and held the primary coil inductance to a few tens of nanohenries, necessary for proper operation of the generator.

Rail guns

Rail guns of various kinds have been around for many years. However, almost all rail guns under study today are built along the lines of those used by R. A. Marshall and his collaborators. Their successful work, reported by Rashleigh and Marshall[15] in 1978, is mainly responsible for the recent resurgence of interest in the field. Figure 8 shows the basic components of a rail gun. The gun's square bore is bounded by upper and lower parallel conducting rails, separated by insulating side walls. Most of the projectiles fired successfully to date have been lexan cubes.

Initially, the projectile is placed in the gun breech, and a thin metallic fuse is placed between the rails near the projectile's rear face. Usually, a thin shock-mitigating insulator (ablator) is taped to

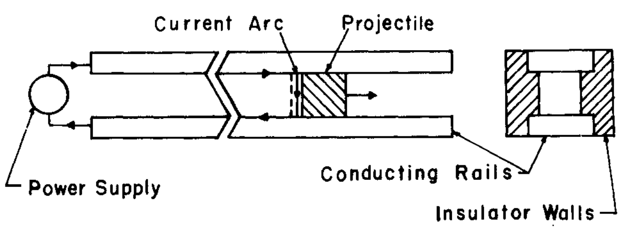

Fig. 8. Two views of a square bore rail gun.

this face. When the power supply is turned on, the metallic fuse quickly vaporizes and a current arc forms behind the ablator. The resulting force on the projectile can be written approximately as

$$F = L'I^2/2 \quad (1)$$

where I is the current flowing through the system and L′ is the rail inductance per unit length. For a square bore L′ is approximately constant and about 0.5 μH/m. Its precise value depends somewhat on the thickness of the rails; the current skin depth, which can vary during a shot; and the presence of nearby conductors. (When the entire rail gun assembly is potted and placed inside a metal pipe for strength, L′ may be reduced significantly.)

Rail gun power sources have included capacitor banks, flux compression generators, and inductive storage coils. Marshall pioneered use of the coils. He used the large Canberra homopolar generator to load an intermediate inductive store, which then was switched into the rail gun. The time constant of this system was long enough to provide nearly constant current during projectile acceleration.

Under Marshall's conditions of nearly constant I and L′, the force on and acceleration of a projectile of mass M and cross section A (bore cross section) also are approximately constant. In one of the most spectacular shots reported by this group, a 12.7 mm (0.5 in.) cube of lexan (weight about 3 g) was accelerated to a velocity of 5.9 km/s in a time of order 1.9 ms. The gun was 5 m long, L′ was about 0.4 μH/m, and the average current was about 250 kA. These data are internally consistent, to within a few percent, with Eqs. 2 and 3 which follow readily from Eq. 1 when M and L′ are constant, and the projectile starts from rest.

$$V = L'/2M \int_0^t I^2 dt \quad (2)$$

$$S = L'/2M \int_0^t dt \int_0^\tau I^2 d\tau \quad (3)$$

The pressure on the projectile, calculated from Eq. 1 and the projectile cross-section, was about 12,000 psi, approximately the static yield strength of lexan. Even so, the projectile was recovered essentially undamaged.

Strip generators are now used to power rail guns in a joint Los Alamos-LLNL program. R. S. Hawke and A. L. Brooks are coordinating program efforts for LLNL, while D. R. Peterson has a major role in the Los Alamos work.

Detailed results of tests carried out to date are given by Hawke et al.[16], so we only summarize the major results.

- A 3 gram (12.7 mm) lexan cube was accelerated to a velocity of 5.5 km/sec.
- A 3 gram (12.7 mm) lexan cube was possibly accelerated to a velocity of about 10 km/sec, but the condition of the projectile is unknown.
- A 165 gram (50 mm) lexan cube was accelerated to a velocity of about 0.35 km/sec.

Diagnostics employed consist of current and breech voltage, magnetic field probes and light pipes located along the gun rails to monitor the projectiles inside the gun, and flash x-rays to photograph the projectiles in free flight.

To date we have been thwarted in our efforts to get good signals from the magnetic probes and light pipes when the projectile velocities exceed a few km/sec. However, signals obtained for the earlier stages of acceleration have been consistent with positions and velocities calculated from Eqs. 2 and 3 from the current records. These equations also predict free flight positions vs time for the projectiles after they exit the gun. The flash x-ray data agreed with these predictions for the first and third results.

Although early interior diagnostics and the current integrals were consistent for the 10 km/sec velocity listed, no projectile images were obtained on the flash x-radiographs. Thus, the result is not confirmed and, indeed, it is possible that the projectile was badly fractured at the end of acceleration. The current for this shot peaked at about 1.2 MA, and therefore produced pressures exceeding the lexan static tensile strength by more than a factor of ten. Further, the current pulse was sufficiently long (> 500 μs) that the projectile was still under considerable stress when it exited the gun. Shots are now scheduled that will employ longer rail guns (12 feet as opposed to 6 feet used to date) - sufficient to allow the projectiles to coast, and presumably, stress-relieve before exiting.

Plasma Focus

The plasma focus project began as an effort to develop an intense, pulsed, expendable neutron radiographic source.

In view of the rapid increase in neutron yield with peak driving current the plasma focus device seemed to be the most logical candidate to achieve large, short pulse yields. For example, a correlation of yields with peak currents, obtained from capacitor bank powered devices located in various laboratories, implies that short pulse yields $\geq 10^{13}$ D-D neutrons should be obtained from a Mather type plasma focus when operated at peak currents of about 10 MA. Tentative calculations indicated that plate generators could be developed capable of supplying such currents, and this has become a major program goal. Since this is a rather speculative endeavor the development of this project would follow a progressive experimental program through increasingly higher current operational levels. This should provide for both development of the larger current, explosive generator power supplies and the physical understanding and development of the very high current plasma focus devices.

The preliminary explosive generator tests were designed to achieve peak currents of ~ 1.5 MA, which were similar to the available currents from our 72 KJ laboratory capacitor bank. The gun geometry selected had a center electrode, anode, diameter of 10.2 cm and an outer electrode ID of 15.2 cm. Initially a pyrex insulator length of .5 cm was used, but this has since been lengthened to 7.6 cm. The plasma focus anode length has been varied between 20.3 cm and 25.4 cm to accommodate the rundown times dictated by the power pulse and initial gas fill pressure.

The diagnostics employed in these experiments included the full complement of electrical characteristics, an extensive array of neutron detectors, and optical image channel-plate intensifier cameras. Most of the neutron diagnostics and the intensifier cameras were implemented by Herald Kruse, Peter Kruse, and Donald Bartram of Los Alamos Group P-14. Currents were monitored on both the generator assembly and the plasma focus header with Rogowsky coils. The gun voltage was measured using a shielded resistive probe with a frequency response of ≤ 500 MHZ. Neutron emission was characterized with activation methods, prompt/time-of-flight detectors, and a one dimensional neutron imaging system. Silver, sulfur, and indium were used for activation measurements of total yield with combined accuracies of a few percent. Prompt and time-of-flight instruments were used to record the reaction history and energy spectra of the neutron yields. The neutron imaging system was used to determine the yield dependence along the plasma focus axis beyond the end of the anode. Finally, and perhaps most importantly, the channel-plate cameras took ≤ 5 ns, end-on optical images of the plasma sheath at two different times during the operation of the gun (Fig. 9), and provided much of the information and many of the clues for correlating other diagnostics into a more unified picture of the experiments.

The plasma focus project has now achieved a neutron yield of $\leq 3 \times 10^{11}$ neutrons/shot with a peak current of 2.4 MA. Yields at lower currents, 1.5 MA, 2.0 MA, and 2.2 MA, agree well with those obtained from capacitively driven systems at similar peak currents. These results would also compare quite well with those of Freiwald and Downing[17]. We have also observed a decrease in the spectral energy spread and a decrease in the full-width half-maximum of neutron prompt history at higher currents. This could imply a shift in neutron production mechanism in the high pressure operating mode, toward a more thermal characteristic, which compares well with the Frascati results[18]. Experiments at yet higher current levels will be necessary to establish this preliminary observation.

In the course of obtaining these results, we have also made some progress toward understanding a number of important mechanisms in the operation of the plasma focus. For example using our laboratory capacitor bank and the channel-plate camera we have been able to distinguish between the low pressure operational mode in which the plasma sheath becomes thicker and more diffuse, and the high pressure mode in which the sheath is thin and quite sharply defined. Also, when we were operating in the low pressure mode the plasma focus performed erratically with large fluctuations in characteristics from shot to shot. In the high pressure mode, machine operation was quite consistent and highly reproducible. From a combination of the capacitor and generator driven experiments the important parameters involved with plasma sheath formation and lift-off dynamics are becoming better defined. An illustration of this is provided by the interrelationship of the early current derivative, the initial fill pressure, and the apparent residual gas remaining behind the plasma sheath. Basically, the observation is that larger current derivatives permit higher fill pressures and reduce the residual gas. This result is in good agreement with Fischer and Haering's[19] observation of coronal discharge characteristics at the time of plasma sheath formation. Also, we were surprised to learn that the sheath expands radially from the end of the insulator more rapidly than elsewhere. Two dimensional calculations, Lindemuth and Freeman[20], have indicated that this behavior is related to the temperature

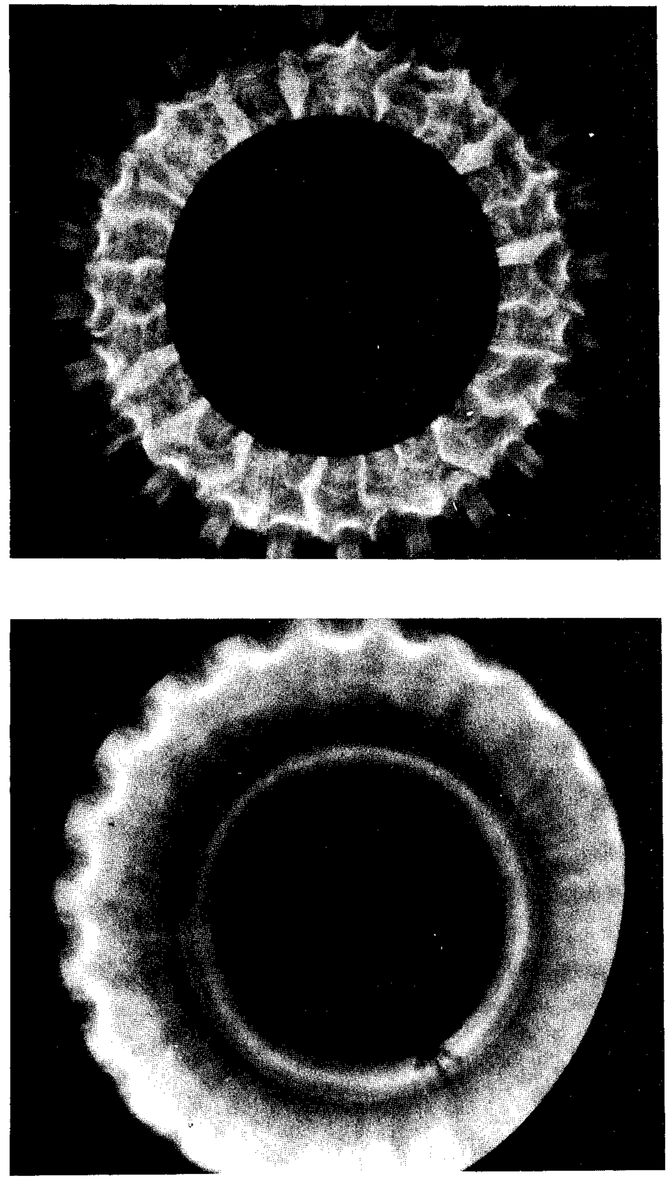

Fig. 9. End-on channel plate photographs of plasma focus taken at different times: upper view, 1 μs after switching; lower view, 3.5 μs after switching.

profile of the current sheath as it begins its radial expansion. In fact, some tentative conclusions based on these observations, as well as from intensifier photographs, indicate that the outward motion of the inverse pinch can be quite rapid.

In a scheduled series of experiments, several of the hypotheses for plasma sheath formation and behavior will be tested. One of the more important of these is the proposed explanation for a restrike phenomenon observed in the breech region of the gun with an operational current of 2.5 MA. There is evidence to support the theory of a reflected shock from the vacuum chamber wall at a radius of 15.2 cm with reinjection of gas into the interelectrode gap at the time of the radial collapse of the current sheath. With this in mind, the vacuum chamber for the explosive generator driven plasma focus has been enlarged to a radius of 33 cm. Given the success of this modification, the current regime of 2.5 - 3.0 MA will be explored to further test our physical understanding of the plasma focus and its neutron scaling characteristics. We are also pursuing the development of opening switches for use with the explosive generators to enhance their efficiency. A useful switch for the plasma focus experiments would interrupt a few megamperes in ≤ 1 μs and remain open for the 3-4 μs pulse delivered to the device. Development of this switch would permit tests in the 5-6 MA region of operation.

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