CONF-800640--8

DEVELOPMENT OF A 50 Hz, 250 kV, 500 ns, 500 KW AVERAGE POWER PULSER*

Malcolm T. Buttram
Sandia National Laboratories, Albuquerque, New Mexico 87185

Summary

This paper describes the development of a 50 Hz research pulser with per shot specifications of 250 kV, 500 ns FWHM, 10 kJ. It is designed for burst mode service. The pulser is a two element Guillemin Type C pulse forming network with two parallel Marx generators serving as the first element and a single Marx generator serving as the second element. This paper will consider the two Marx generators of the first element only and will outline the important ongoing developmental areas.

Each generator has a 500 kV output voltage and stores 5 kJ. Two units in parallel are required to achieve the low inductance for a 10 kJ, 500 ns output pulse. Each Marx generator has 8 capacitor stages and four spark gap switches. The switches are cylindrical sulfur hexafluoride insulated trigatrons with vortex purge gas flow. Initial observations are that very little gas flow is required for 50 Hz operation at 50 kV across the switch and 20 kA peak current in a 50 shot burst.

The first switch of one Marx generator is triggered. The first switch of the second Marx is triggered by the breakdown of the first switch of the first Marx. The trigger pins in the second gaps are capacitively coupled to ground. The trigger pins of final gaps are capacitively coupled to earlier stages. For a single generator the delay from triggering of the first gap to full Marx generator erection is 100 to 150 ns. Parallel operation of the two Marx generators is achieved for at least 85 percent of all shots. To increase this to 100 percent may require a better triggering system. Present limitations on the operation of the device come from solid dielectric failure and variation of spark gap self breakdown thresholds.

Introduction

This paper describes the design and development to date of a 250 kV, 500 ns, 50 Hz burst mode pulser. The device is a prototype of a larger system to be constructed from the modules developed in the prototype program. Each module is a 500 kV, 5 kJ Marx generator with sufficiently low inductance for 500 ns output. Several of these Marx generators operated in parallel would form the first stage of a Guillemin Type C[1] pulse forming network (PFN). Subsequent stages would also be 500 kV Marx generators but with substantially lower stored energy. The prototype consists of two of the 500 kV, 5 kJ Marx generators.

The choice of such a system was dictated largely by the need to produce a 500 ns pulse with devices of minimal complexity which could be operated in parallel for higher energy per pulse. A 500 ns pulse length is rather short for a PFN and rather long for a distributed pulse forming line (PFL). For example a water PFL for this application would be 8.3 meters long. Long (> 1 μs) water lines produce acceptable pulses[2]; however, they are bulky and they require a difficult output switch development program. Both the bulk and switch problems can be avoided by going to a PFN.

*This work was supported by the U.S. Dept. of Energy, under Contract DE-AC04-76-DP00789.

A PFN followed by a step up transformer is not attractive for this regime. The load impedance per module is 6.25 Ω. Assuming the PFN is charged to a reasonable voltage of 100 kV, the transformer voltage gain is 5 and the PFN impedance is 0.25 Ω. For a reasonable output pulse (rise and fall times 100 ns) the transformer coupling constant would have to exceed 0.97. The 50 kV transformer primary switch would operate at 50 Hz, 200 kA and have an inductance less than 50 nH. Four switches to be operated in parallel could be designed for this latter function; however, the coupling requirement is a formidable constraint.

The final option considered is a 250 kV PFN constructed from 500 kV Marx generators. This is most easily done in the Guillemin Type C configuration of Fig. 1a which of all the Gullemin networks has the lowest inductance, a pivotal consideration in the design of a pulse length (inductance) limited device. Contrast, for example, the Type A configuration of Fig. 1b which has often been used to produce microsecond pulses at several hundred kilovolts.[3,4] In the Type A the first stage (L_1, C_1) is a Marx generator, the subsequent stages, which are initially uncharged in this modification of the original Guillemin design, are used to shape the Marx discharge. As indicated by Table I the inductance of the first stage Marx generator is 244 nH which is extremely small for a 500 kV device. The first stage of a Type C PFN is 791 nH. Furthermore, the inductance of later stages increases for the Type C circuit while it decreases in the Type A.

TABLE I

Parameters of the First Three Stages of Guillemin Networks for 500 ns, 6.25 Ω Output

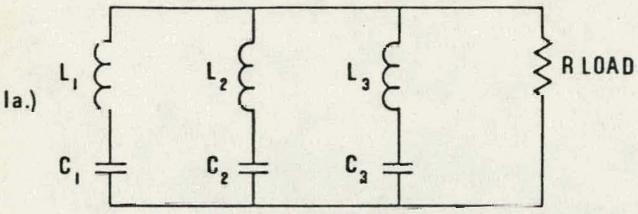
	Type C	Type A
L_1	791 nH	244 nH
C_1	32 nF	37 nF
L_2	844 nH	279 nH
C_2	3 nF	19 nF
L_3	1147 nH	63 nH
C_3	1 nF	21 nF

Design

A Marx module is shown schematically in Fig. 2. Eight 0.3 μf capacitors, each charged to 62.5 kV for 500 kV operation, are arranged in two opposed rows of four each. The space between the rows is approximately 4 cm which is also the spacing between the high voltage and ground connections of the generator. This arrangement minimizes the generator inductance by allowing the Marx current to pass over the top of the capacitors at as close a spacing as is consistent with high voltage insulation (in transformer oil) requirements. Figure 3 illustrates the importance of properly positioning this current path. Figure 3a shows the current waveform when a single capacitor is shorted with a 10 cm wide strap across the top, i.e., via the shortest path between its tabs. (The "top" of the capacitor is by definition the end close to the tabs, the abutted ends in the Fig. 2.) The resistance and inductance calculated for this waveform are given in Table II together with values from Fig. 3b and 3c which are for short circuits where the strap runs along the side and bottom of the capacitor respectively. For a Guillemin

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.



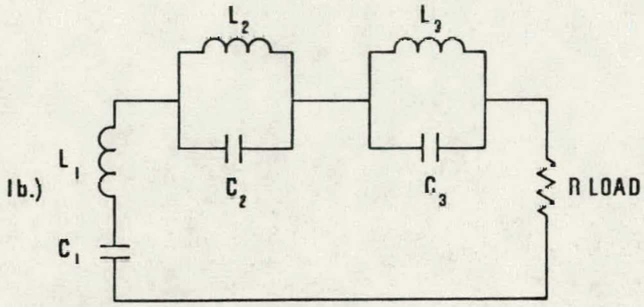


Fig. 1. Guillemin networks.
a. Type C.
b. Type A.

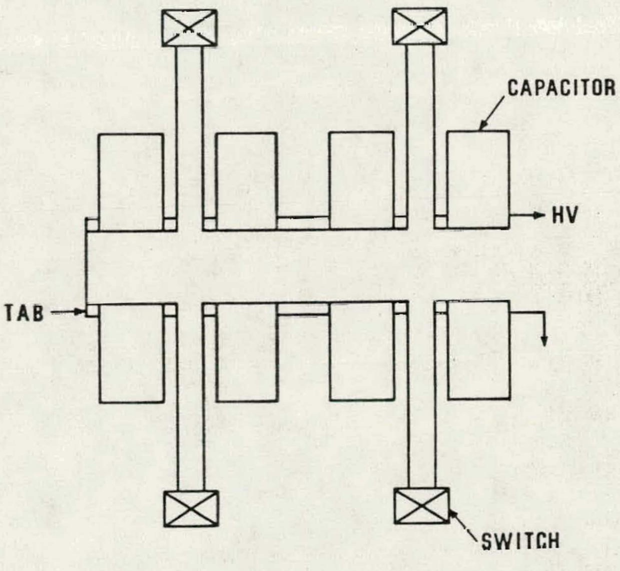
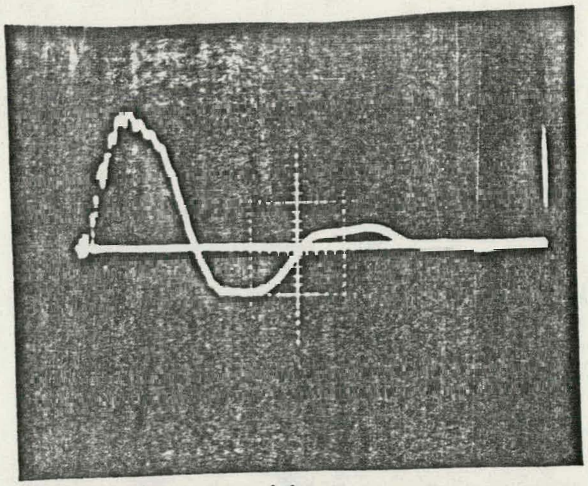
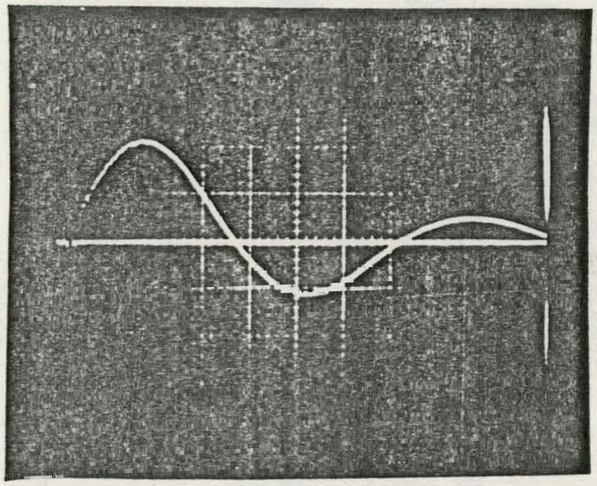


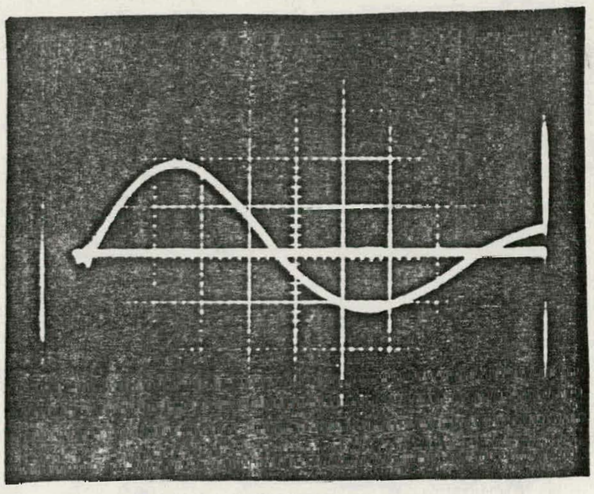
Fig. 2. Schematic of one Marx generator unit illustrating the geometry.



(a)



(b)



(c)

Fig. 3. Short circuit ringing current waveforms from a single capcitor charged to 1 kV.
a. Top strap.
b. Side strap.
c. Bottom strap.
(200 μs/div, 1 kA/div)

TABLE II

Inductance and Resistance for a Single Marx Capacitor (C = 0.3 μf, L = 25 nH nominal) for Various Shorting Strap Locations

Strap Location	L	R
Top	66 nH	0.25 Ω
Side	162 nH	0.32 Ω
Bottom	253 nH	0.5 Ω

Type C PFN, the output pulse duration is half the ringing period of the first element. If half the ringing period of a single capacitor exceeds 500 ns, the total Marx generator half period will exceed 500 ns. Therefore the configuration of Fig. 3a, which is the only one with a half period less than 500 ns, is the only acceptable configuration. Figure 3c corresponds to a Marx configuration in which the capacitor bottoms are abutted. This arrangement while geometrically more convenient from the point of view of switch attachment is unusable because of its added inductance. Note that the capacitor has an internal resistance in the range of 0.3 Ω. The series combination of eight capacitors has a measured resistance of 2 to 2.5 Ω which causes a significant loss when the load is 6.25 Ω.

The switches in this geometry are mounted approximately 36 cm from the capacitor tabs as shown in Fig. 2. The transmission line between the tabs and switch is 1.3 cm thick and 10 cm wide. The thickness may have to be increased as will be discussed below. A switch is shown diagramatically in Fig. 4. All four switches are trigatrons with rather large area trigger electrodes. A re-entrant geometry (cylindrical electrode coaxial with cylindrical housing) was chosen to permit an enhanced length of flashover surface to be inserted as illustrated by the dashed lines in the figure. In practice this was found unnecessary to ± 75 kV charge and lip on the insulator is provided for mechanial positioning only.

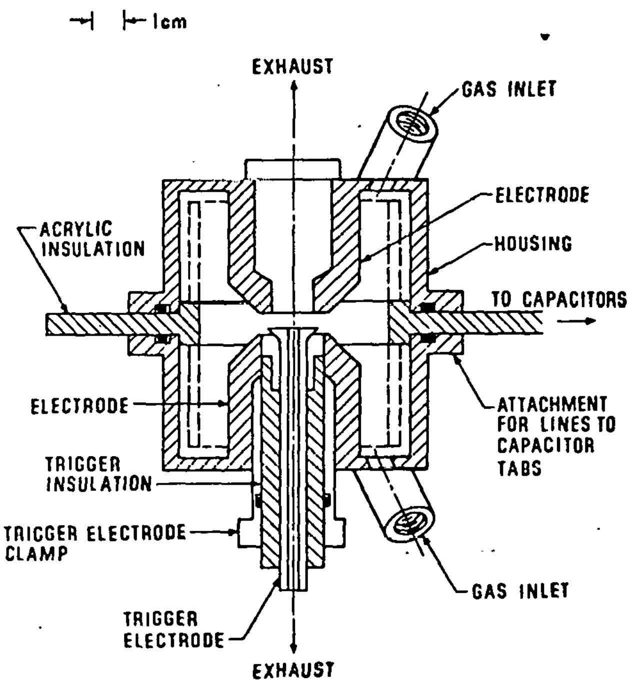


Fig. 4. Schematic cross-section of a Marx switch.

The total inductance of the generator, exclusive of load connections is made of the four parts listed in Table III. The central transmission line (area between the rows) and the tab-to-switch connections are modeled as parallel plate transmission lines 61 cm x 3.8 cm x 20 cm wide and 36 cm x 10 cm x 1.3 cm wide respectively. The switch is modeled as concentric cylinders plus the spark inductance.[5] The capacitor inductance is from Table II, row 1. The computed inductance is 708 nH and the measured inductance is 730 nH which is compatible with the Guillemin Type C requirement of Table I.

TABLE III

Calculated Inductance for Various Marx Generator Parts

Source	Inductance per Element	Total Addition to Marx Inductance
Central transmission line	144 nH	144 nH
Tab-to-switch connection	56	224
Switch	19	76
Capacitors	66	264
Total		708

Switches

A switch is shown in Fig. 4. It is a cylindrical unit with 7 cm ID and 3.8 cm electrodes. Sulfur hexafluoride insulation is used. The switch is purged by injecting gas with a rotary motion as shown in the figure and exhausting through the center of the trigger pin and the opposite electrode. The trigger pin is epoxyed into an acrylic sleeve which is held within one of the electrodes by an "O"-ring clamp. The two halves of the switch and the insulator are held together by an external clamp not shown in the figure. The necessity to align and seal the switch without the benefit of bolts through the insulator (which are prone to surface flashover) led to the decision to use a trigatron rather than a mid-plane spark gap. In retrospect, a three element gap could have been fabricated by encapsulating the gap in epoxy (exclusive of holes for electrode removal). The encapsulant would serve as a pressure seal. The spark gaps may be reconfigured to a mid plane of this type in the future. As built, the spark gaps may be operated safely to 100 psig with a typical working pressure being less than 70 psig.

The spark gaps are weakly purged. Extensive studies of the free (unpurged) recovery of spark gaps in air and SF_6 indicate that at least 80 percent of the dielectric strength is recovered within 20 ms[6,7] even for substantial discharge currents and long pulse durations (> 200 kA, > 1 μs). Experiments with the RTF-I pulser[8] demonstrate that 20 kA discharges will quench at a 40 Hz repetition rate with no spark gap purging. This process can not continue indefinitely as the gap requires some cooling and with no gas flow will ultimately become hot enough to melt its insulation. Initial experiments indicate that for ± 30 kV, 20 kA operation the present gaps will quench for a 50 shot burst at 50 Hz with negligible gas flow (less than 3 SCFM per switch). There is some concern whether this is still true at ± 62.5 kV, 40 kA. The situation is confused somewhat by the failure of the spark gaps to maintain a well defined self-break threshold even under single shot conditions. Figure 5 shows the cumulative probability of breakdown as a function of voltage below the maximum observed breakdown voltage V_{max} for a single switch in a single

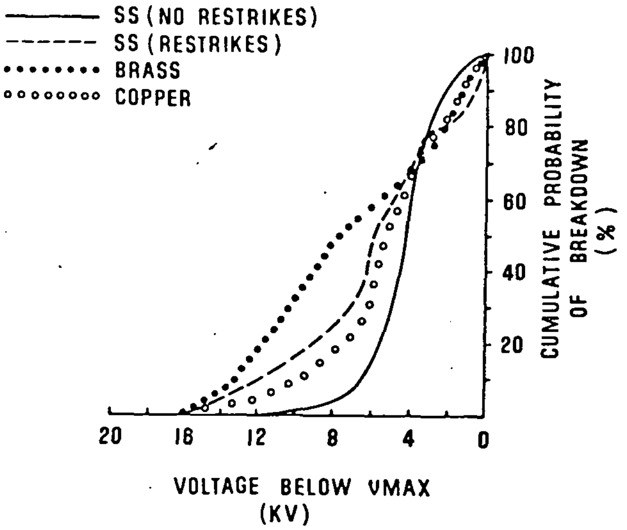


Fig. 5. Cumlative probability of breakdown for various electrode materials as a function of voltage below peak breakdown voltage (V_{max}).

shot mode. V_{max} is in the range 50 to 60 kV. Typical data samples of 40 to 60 shots show a measurable breakdown probability to 16 kV below V_{max} (almost 70 percent of self-break) for copper and brass electrodes. For a system with 8 spark gaps, a 5 percent chance of one gap failing translates to a 34 percent chance of a prefire on a given shot. This has been documented and attributed to changes in the electrode surface for discharges in air using copper and stainless steel electrodes.[9,10] In the data of Ref. 9 the breakdown spread is somewhat less for stainless steel than for copper and the same is true for the data of Fig. 5. (The stainless steel no-restrikes curve applies.) The situation is complicated by aging effects as indicated by the stainless steel-with restrikes curve. In the no restrike case each breakdown was a single shot, in the restrike case each breakdown led to multiple arcs and more severe surface damage. In the latter case the cumulative breakdown proability with stainless steel is similar to the copper data (without restrikes). A study of this process is in progress.

Assembly

The entire prototype assembly is contained in a 1.2 x 1.2 x 0.9 m^3 tank of transformer oil together with trigger, trigger power supply, and monitors. The generators are mounted so that the plane of Fig. 2 is the horizontal, with one generator atop the other, separated by 3 cm of acrylic insulation. The trigger is a small air core transformer with a typical output of 100 kV. The triggered electrode is positive and the trigatron gap breaks down on the positive swing of the trigger pulse. The Marx generators are charged resistively through two 4 to 10 KΩ flowing water resistors from a ± 80 kV, 2 MW power supply.

Operation - One Marx Generator

A schmatic for one Marx generator including a typical trigger connection scheme is shown in Fig. 6. The first gap is triggered, the trigger electrode of the second is capacitively coupled to ground, and the triggers of the remaining switches are capacitively coupled to earlier stages. Stacks of barium titanate

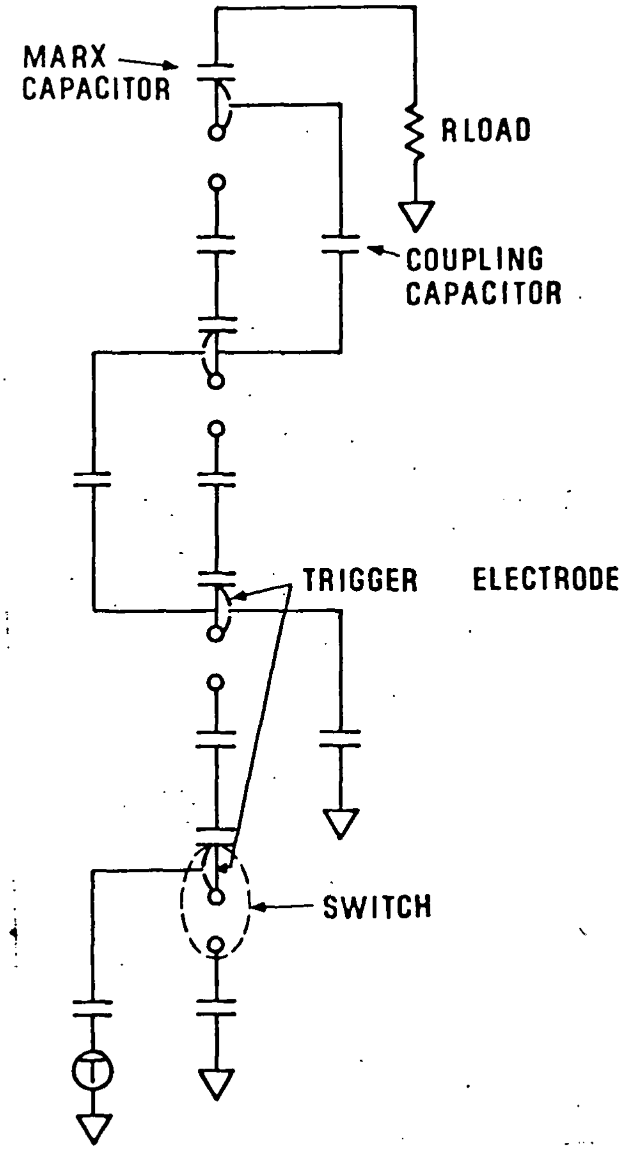


Fig. 6. Schematic of one Marx generator showing trigger coupling.

capacitors are used for these couplings. The spark gaps, particularly the second, do not trigger as reliably if resistors are substituted for these coupling capacitors. With this configuration when the first gap fires the entire Marx generator erects with > 95 percent probability. For 0.64 cm spacing the first gap triggers reliably to at least 70 percent of self-break with the triggering electrode flush with surrounding electrode. For larger gap spacings the trigger must be inserted into the gap, the greater the insertion the greater the triggering range. Typically for a 1 cm gap an insertion of 1.5 mm is appropriate and the gap will trigger from ± 40 kV charge voltage upward. The triggering range extends below 60 percent of self-breakdown from 50 kV upward. Total delay increases with decreasing percent of self-break but is generally in the range of 100-200 ns. For operation below ± 30 kV charge, the Marx operates to 50 Hz in a 1 second burst without problems. Above 50 kV stable operation has been achieved to 10 Hz but is limited by the ill defined self-break threshold previously discussed and by occasional failure of the solid insulation. This latter failure occurs invariably in gap 3. The spark gap firing sequence is 1, 2, 4, 3 so that gap 3 briefly supports some fraction of the total generator voltage (certainly more than twice the charge voltage). When spark gap 3 fires a 200 MHz standing wave pattern with a node at the switch and a maximum at the tab end is setup in the transmission line leading to the capacitor tabs. This breaks the insulation at the open end of the line. The failure is probably due to cumulative damage as several hundred or thousand shots are typically required to get a failure. An attempt is underway to decrease the over volting of gap 3 by decreasing Marx erection time. That failing the insulation thickness must be increased with a corresponding increase in inductance.

Operation - Two Marx Generators

Parallel operation of two generators has been achieved with capacitive coupling between corresponding trigger electrodes of the two generators. Thus as the triggered generator erects, it triggers the spark gaps of the second Marx generator. This coupling scheme is illustrated in Fig. 7. The left generator is triggered as indicated by the trigger generator shown in the figure. The coupling of the remaining trigger electrodes of the left Marx generator is as in Fig. 6. The trigger electrodes of the right generator are coupled to the corresponding main (not trigger) electrodes of the left Marx through barium titanate capacitor strings. With this scheme the trigger electrodes of the right Marx generator fire when the left Marx erects. This does not automatically cause the right Marx generator to erect.[11] If, for example, all the gaps of the left Marx have closed but none have closed in the right generator then the left generator will raise the output end of the right generator to 500 kV. It does so by providing current to charge the capacitance of the right generator spark gaps to a value such that the sum of the capacitor and spark gap voltages is 500 kV. Obviously this leaves the spark gaps with no voltage so that the right generator appears to have erected even though the spark gaps have not closed. The time to charge the right Marx as governed by the inductance of the generators (2 x 700 nH) and the spark gap capacitances (100 pF/8) is 13 ns. This process will almost certainly interfere with erection of the right Marx generator independent of the number of its gaps which may have broken down prior to complete erection of the left generator. In the present system this problem is avoided because the first Marx generator to erect is substantially loaded down by the load resistance. It charges the second Marx to perhaps 250 kV. If two spark gaps of the second Marx have closed the remaining gaps have sufficient voltage to close. Figure 8a shows typical output waveforms from two Marx generators into an overmatched load. The voltage (upper trace) is 420 kV. The current (lower trace) of 24 kA is from the lower generator only. Total current is 48 kA. Load impedance is 8.8 Ω.

Figure 8b shows a misfire in which the triggered generator erects, deposits its energy into the load and the second generator erects afterward. The probability of such a misfire increases as the spark gaps are operated farther from self-break with a consequently longer erection delay. In a typical 10 kJ operating regime the misfire probability is less than 15 percent; reducing this to 1 percent level may require an improved trigger system.

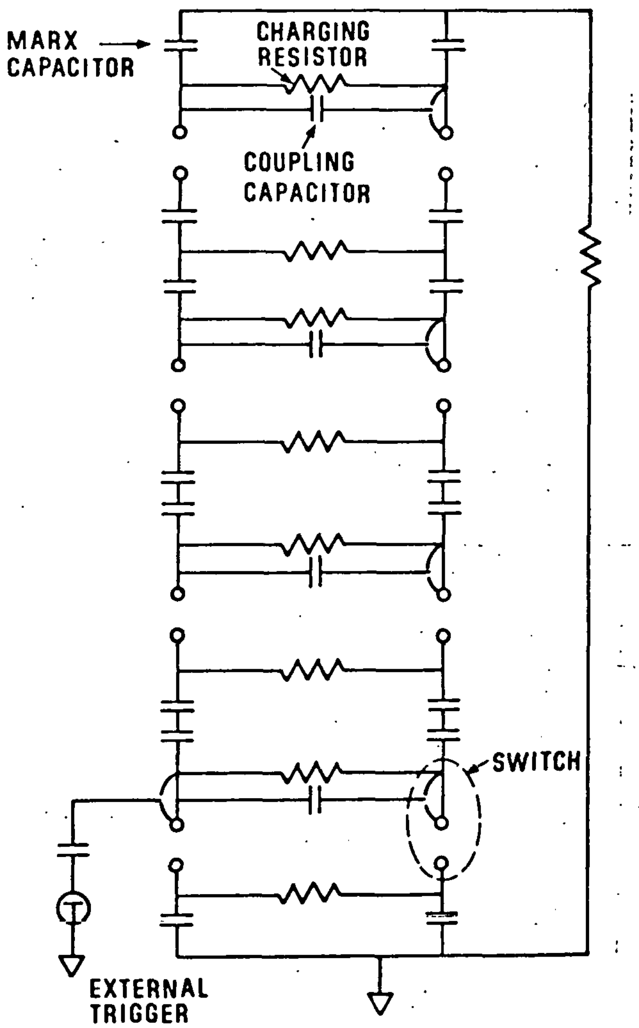
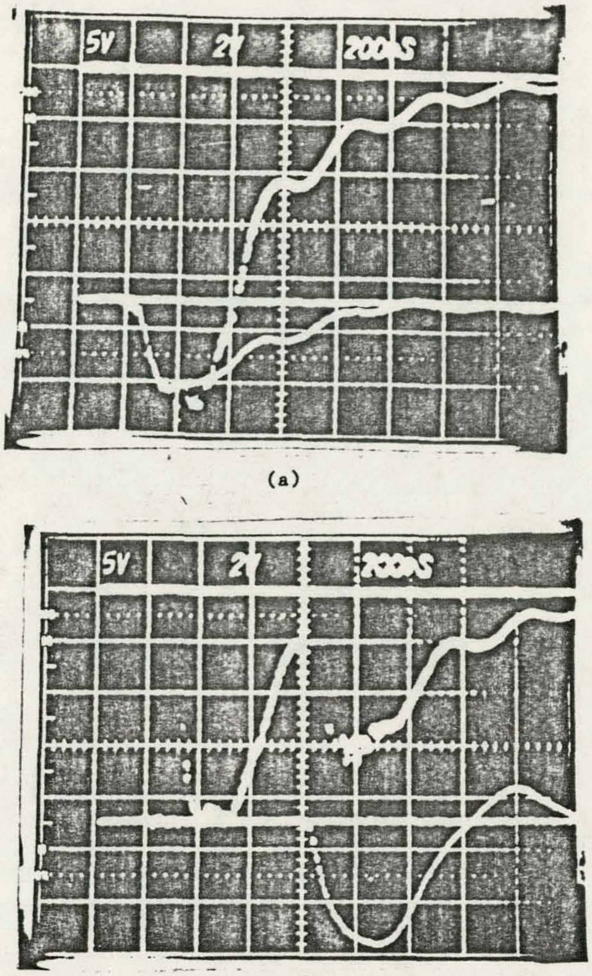


Fig. 7. Schematic of two parallel Marx generators illustrating the cross-coupling scheme used for triggering.



(a)

(b)

Fig. 8. Waveforms from two Marx generators into a resistive water load. Upper trace, voltage (64 kV/div), lower trace current from the untriggered generator (20 kA/div).
a. Proper operation.
b. Misfire.

Conclusions

Data demonstrate that the Marx generator based Gullemin Type C PFN described in this paper is capable of delivering 10 kJ of pulsed energy to a load in in 500 ns at 250 kV. The desired repetition frequency can be achieved at half voltage but substantial work remains to be done to achieve full repetition rate at full voltage. Problems encountered include the failure of solid dielectric insulation due to Marx generator erection transients and a failure of the spark gaps to maintain a stable self-break threshold.

Acknowledgments

The author wishes to thank K. R. Prestwich for his assistance in all phases of this effort. W. Crowe and J. P. Corley have done the bulk of the mechanical assembly and have contributed to many other aspects of the project.

References

1. Glasoe and Lebacqz, Pulse Generators, MIT Radiation Laboratory Series, McGraw Hill, NY, 1948.

2. J. J. Ramirez, Sandia National Laboratories, private communication.

3. C. V. Duncan and L. P. Bradley, Proc. of the Int'l. Pulsed Power Conf., Lubbock, TX, 1976, Paper ID-3.

4. J. J. Ramirez, K. R. Prestwich, R. S. Clark and M. T. Buttram, Proc. of the 2nd Int'l. Topical Conf. on High Power Electron and Ion Beam Research and Technology, Ithaca, NY, 1977, Vol. II, p. 891.

5. J. C. Martin, AWRE Report SSWA/JCM/1065/25, unpublished.

6. R. J. Churchill, A. B. Parker and J. D. Craggs, J. of Electronics and Control, 11, 17 (1961).

7. J. A. Philosophos and M. B. Robinson, Insulation/ Circuits, April, 1979, p. 48.

8. M. T. Buttram and G. J. Rohwein, Proc. of the 2nd Int'l. Topical Conf. on High Power Electron and Ion Beam Research and Technology, Ithaca, NY, 1977, Vol. II, p. 845.

9. V. A. Aurutskii, Sov. Phys. Tech. Phys. 18, 389 (1973).

10. V.A.Aurutskii, G.M.Goncharenko and E.N.Prokhorov, Sov. Phys. Tech. Phys., 18 386 (1973).

11. T. H. Martin, Sandia National Laboratories, private communication.