A 480 JOULE, 650 kV, < 3 ns RISETIME, 500 ns PULSE WIDTH, COMPACT PULSE GENERATOR

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Abstract

The experimental results of a 32-stage Marx generator are presented. A pulse forming network (PFN) was added to each stage of the Marx to lengthen the pulse width to 500 ns. The "PSpice" simulation shows that PFN-Marx generator can be reduced to the basic circuit of a discharge line pulse generator. The system is designed for a load in the range of 300 to 700 Ω. To achieve the steep rise in the voltage pulse and meet a low jitter requirement, UV-coupled spark gap switches are employed in the system. With an added pulse sharpening technique, it is possible to reduce the risetime to a few nanoseconds, or to several hundreds picoseconds if it is required.

When completed this generator will be able to energize the "Super-Reltron" 1.3 GHz tube (150 kV injector voltage, 500 kV accelerating voltage and current of ~ 1 kA) of Miller *et al* [1], the gyrotron-backward wave oscillator (voltage of 700-800 kV, current of 1-4 kA at frequency 4.6-6 GHz) of Gilgenbach *et al* [2], and the gyratrons (500 keV beams, current 0.7 kA at frequency of 20 GHz in the $E_{0,1}$ mode) of Bratman *et al* [3].

Introduction

Marx generators have been at the core of pulsed power research for many years. Most high energy, high voltage, single-shot devices use this mode of generation because of its reliability and versatility. With the growing importance of high power microwave generation, there is a growing need to produce high energy pulses with near "square" shape which have a duration of several hundred nanoseconds.

The classical Marx generator nominally produces the pulse in the form of the double exponential function. The idea to be discussed is to replace the condensers in the Marx system with a pulse forming network (PFN). A great deal of work has been reported in the literature on the PFNs of the Guillemin (A to F) type, which are usually placed in cascade after the Marx generator. Clark *et al* [4] and Ranon *et al* [5], amongst others, describe the applications of the Guillemin networks at low (<120 kV) voltage, and Bernstein *et al* [6] give important data on the generation of long (>300 ns) duration pulses at high (~1 MV) voltage levels.

In this work, the classical PFN is used as a primary energy storage. The idea is attractive for several reasons: the system can be constructed with great precision, it can achieve very high

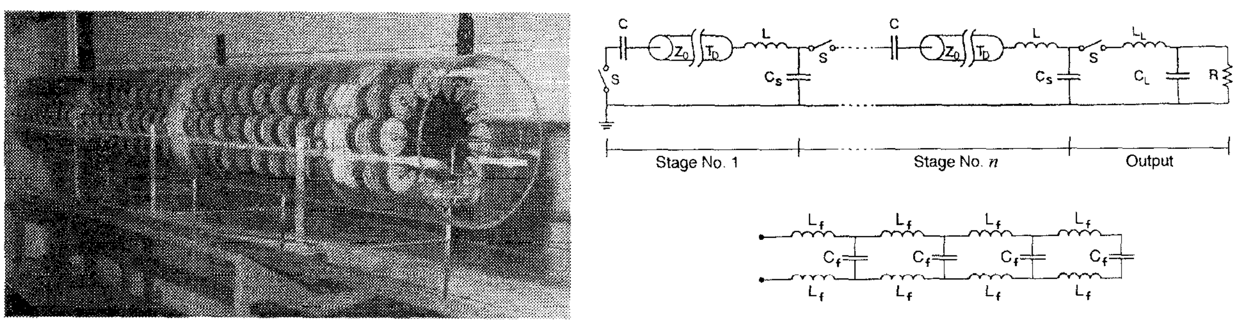

Fig. 1 Left: Stage assembly (prototype) of 32 stage PFN-Marx generator.
Right Top: schematic of the Marx **Right Bottom**: PFN

energy efficiency, and it has a smaller fault-made impact compared to the Guillemin networks. In practice, we find the current arrangement to be very robust, seldom failing to work, and it is versatile. It can be designed to power a variety of loads from 10's Ω found in the vircators to nearly 1000 Ω observed in the gyratrons.

This paper will briefly look at one of the PFN-Marx generators currently under development at the National Research Council of Canada and will explain the concepts of its design.

Modelling

The experimental and computer modelling of the performance of several coaxial line Marx generators were presented by Kekez *et al* [7-9] and the geometrical arrangement of the Marx generator used by Kekez [7] was adopted. The Marx generator (Fig. 1 (top)) can be viewed as a distributed transmission-storage line, consisting of 32 cascaded stages. Each stage has C (2 nF, 40 kV, TDK capacitor) as its energy storage. The return current path is the metallic enclosure, which, together with the finite dimensions of capacitor, C, and with connecting leads, forms a transmission line with characteristic impedance Z_0 that has a transit time of T_D. For each stage, a UV preionized spark gap switch, S, with associate series inductance, L, and stray capacitance of the spark gap electrode with respect to ground were considered. All the stages in the system were erected in a sequential manner at the time interval, t_0. Following the work by Kekez *et al* [8], the experimental values of t_0 from 0.85 ns to 1.20 ns were adopted in the simulation.

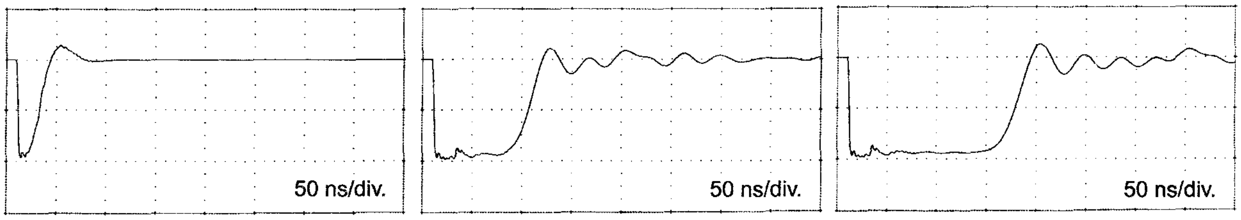

Fig. 2 PSpice simulation of 8 stage PFN-Marx generator with:

left: Marx's characteristics are C_s=8.5 pF, L=50 nH, C=2 nF, Z_0=20 Ω, T_d=0.28 ns, t_0=0.85 ns and R_{switch}=0.5 Ω. The load has C_l=10 nF, L_l= 40 nH, R=36.78 Ω

middle: as in left, but PFN is added. PFN contains 4 C_f and 8 L_f. The inductors, L_f are placed on both side of capacitor, C_f. The numerical values are C_f=2nF and L_f=20 nH. The load matching condition is taken: $R=Z=8(2L_f/C_f)^{1/2}$=36.78 Ω

right: as in middle, but PFN contains 8 C_f and 16 L_f. The load matching condition is also taken: R=36.78 Ω.

With this formulation, the PSpice simulations were carried out and the results are given in Fig. 2. The PFN is attached in parallel to every capacitor, C, of the Marx and close examination of Fig. 2 suggests that, the features of the PFN-Marx system can be approximated by the simplest type of pulse generator. In our interpretation the PFN-Marx, illustrated in Fig. 3, can be presented as an open ended length of the transmission line charged through a high resistor to an equivalent D.C. potential nV. Here, V is the charging voltage of the stage and n is the number of stages. The internal impedance of the generator is nZ, where Z is the characteristic impedance of the stage ($(L_F/C_f)^{1/2}$ with $L_F=2L_f$ as defined in Fig. 1 (bottom)). The line is

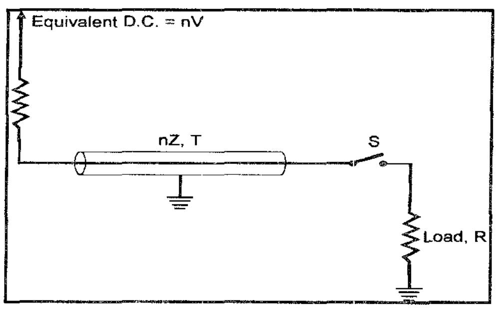

Fig. 3 Equivalent circuit of PFN-Marx generator.

discharged into a load resistor, R, by a switch, S and a single "square" shaped pulse follows if the load, R, is equal to nZ. The amplitude of the pulse is nV/2 and the width, T, is governed by a single stage: ($T=2(n_L L_f n_C C_f)^{1/2}$), where n_L and n_C are the number of coils and condensers in the stage respectively.

Design and Experimental data

The system was designed to operate with the parameters given in Table I

Table I.

Output voltage	200-650 kV
Load resistance	300-700 Ω
Pulse width	400-500 ns
Rise time	4-40 ns
Charging voltage	≤ 40 kV

If the charging voltage is 40 kV, then the energy stored in the 32 stage-PFN-Marx (= $CV^2/2$) would be 488 J. At present, the system (prototype) was tested under single-shot conditions, the spark gaps were operating in atmospheric air, and the output voltage was obtained for a low (200-300 kV) voltage range. To achieve a repetition rate of 10 Hz, charging inductors will be used to replace the current chains of charging resistors. The ideas of O'Malley and Buttram [10] will be applied in designing these inductors.

A great deal of attention was dedicated to a single PFN stage. After being computer modeled, several variations of it were built and tested. The goal is to achieve simplicity in construction, and the variation adopted is given in Fig. 4. Lexan was used to position the capacitors and provide the pattern to "embroider" the inductors.

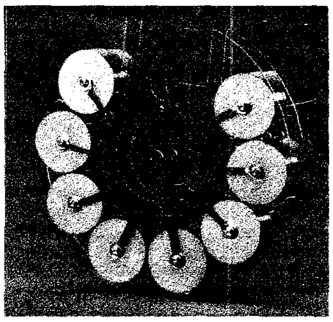

Fig. 4 Single stage PFN containing 8 TDK capacitors (each 2 nF, 40 kV) and 14 inductors (each 0.24 μH). The leads from PFN to the Marx form two additional inductors.

A Physics International: PIM-197A-1 probe with 33 kΩ (18 inch long Carborundum) resistor attached to the input of the probe was used to obtain the results from 32 stages, illustrated in Figs. 5 and 6. A 33 kΩ resistor replaced the $CuSO_4$ resistor that was originally supplied. With this probe, the risetime of the voltage pulse was measured above 10 ns. 24 inch long Carborundum resistors were used as a load. When the value of the resistor was increased from 300 to 900 Ω, the risetime (named "fall") of the output pulse also increased. The data given in Figs. 5 and 6 are used to produce Fig. 7. The straight (regression curve) line indicates that the parasitic capacitance of Carborundum resistors is constant in respect to the ground. These resistors, of the value R, are of the same geometry; therefore, they have the same parasitic capacitance, C_L.

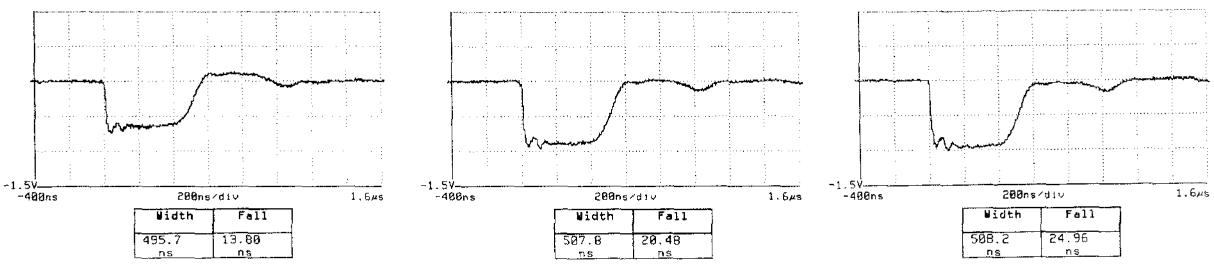

Fig. 5 Voltage waveforms of 32 stage PFN-Marx generator containing 288 capacitors. The voltage was measured across (24 inch long) Carborundum resistors. The following value of the resistors were used: **left:** 300 Ω **middle:** 450 Ω **right:** 500 Ω

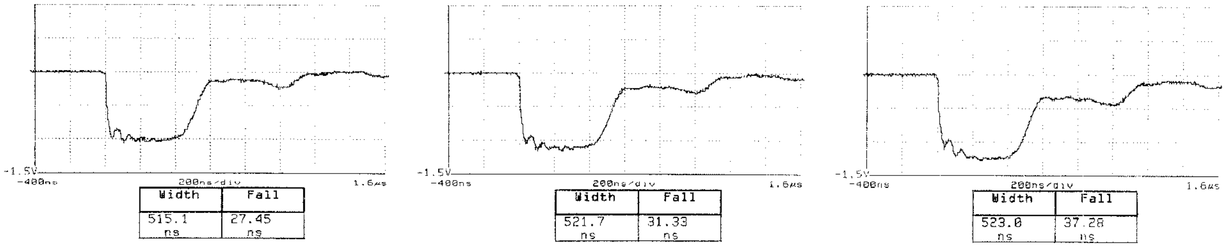

Fig. 6 As in Fig. 5, but for the following value of the resistors:
left: 600 Ω **middle:** 700 Ω **right:** 900 Ω

Fig. 7 shows that the risetime is proportional to RC_L, confirming that the data given in Figs. 5 and 6 are self-consistent. If the driver would be required to energize a backward wave oscillator that typically has an impedance of 120 Ω, the present lay-out can readily be modified to meet this requirement by decreasing the inductance, L_F, in each stage. In this case, we find that the risetime of the system would fall below 1 ns, providing that the multi-spark gap arrangements are adopted, as used in the Rim-Fire generator by Kekez [9].

To produce a pure resistive load, a transmission line (in the form of rod parallel to infinite plane of impedance of 217 Ω and 2.6 m long) with termination on the far end was attached to the generator. During the risetime, the true shape of the pulse was obtained using a wideband (300 kHz to 3 GHz) capacitive E-field device. To evaluate how much the risetime of the PFN-Marx can be improved, a peaking circuit described by Kekez *et al* [8] was placed at the output of the generator, and this peaking circuit has caused the risetime of the output pulse to be enhanced from 8-10 ns in the PFN-Marx to 1-4 ns. See Fig. 8.

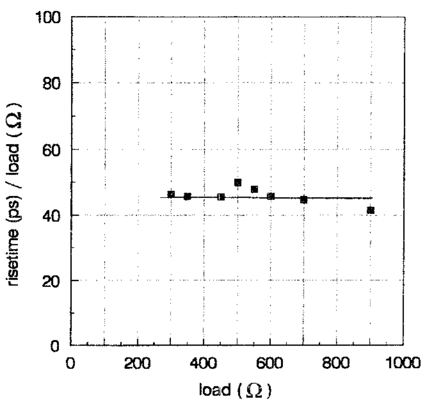

Fig. 7 Ratio of the rise-time and the load resistor *vs* load.

The major concern in the design was to ensure a "smooth" interaction between the Marx and the PFNs in respect to the enclosure. In the PSpice simulations, this effect is represented by the value of the parameters: C_s and Z_0. Both the modelling and experimental work indicate that Z_0 should have an optimum (small) value if the amplitude of oscillation, superimposed on the flat portion of the pulse, is to be suppressed. In the simulation, this is achieved if $Z_0 \leq 20\ \Omega$ as indicated in Fig. 2 (middle). In practice, a small value of Z_0 corresponds to: (a) a close proximity of the spark gaps to the metallic enclosure of the return current path and (b) the use of large cross-sectional area leads that are joining the circuit elements used in Fig 2 (top). If the separation between the spark gaps and the metallic enclosure is large (3.5 inch), the output voltage waveform will have an overshoot as indicated in Fig. 9. With small (1.75 inch) separation, the top trace given in Fig. 9 was measured.

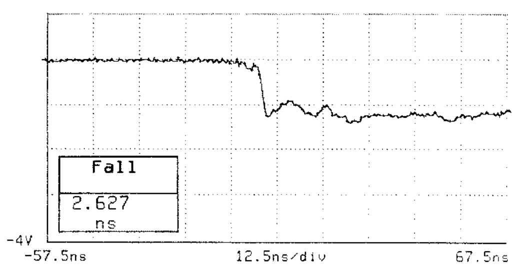

Fig. 8 Output voltage pulse with the peaking circuit

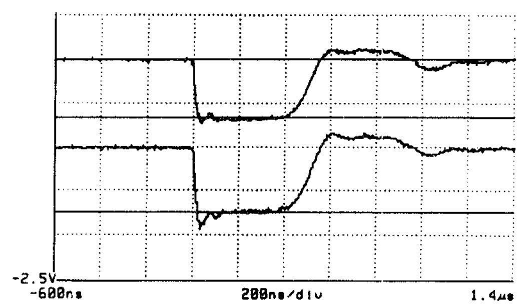

Fig. 9 Effect of the position of return ground lead

For repetitive operation, it is desirable to obtain efficient source. To estimate the energy that could be supplied to the microwave device, the energy efficiency was measured and given in Fig. 10. These results marked by square points (top) and the circular points (bottom) are defined as:

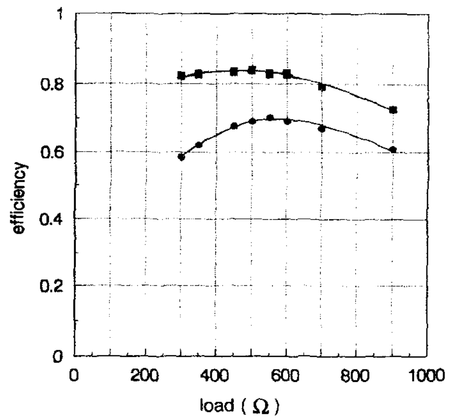

Fig. 10 Energy efficiency of PFN Marx as a function of the load.

$$\frac{\int_{\text{rise time}}^{400\ \text{ns}} (V_{out}\, I_{out})\, dt}{\int_0^{\infty} (V_{out}\, I_{out})\, dt}$$

$$\frac{\int_{\text{rise time}}^{400\ \text{ns}} (V_{out}\, I_{out})\, dt}{\frac{CV^2}{2}}$$

Here, I_{out} is V_{out}/R, and R is the load. When the system would be activated at high (600 kV) voltage range, it is expected that the efficiency would rise because the relative contribution of the Ohmic losses in the spark gaps would fall.

Conclusions

The system described can generate "square" pulse and has the versatility to drive a variety of loads in the high (300 to 700 Ω) impedance range. The energy efficiency of the system was determined (≤ 75%) at low (200-300 kV) voltage range and over the time interval when the pulse is semi-flat.

To have an extra "cushion" at high (>600 kV) voltage range, the present system will be expanded from 32 stages to 36 stages. More attention will also be paid towards the crucial feature: a "smooth" matching in the geometrical arrangement between the ground lead, PFNs and the switching gaps in order to accomplish a "smooth" waveform as if the system would have a "snubber" stage.

Our system does not require a crowbar (diverter) switch and there is no danger to the capacitors as result of voltage reversal and to the potential arcing across the inductors. When the diverter switch is employed, special measures must be taken to safeguard electronics from severe EMI environment. Joitly *et al* [11] give an excellent example how to protect the Marx generator with crowbar switch from accidental overstress at high voltages and offer important data pertaining to the behaviour of the oil-vacuum interface.

At present, there are several approaches to create a compact, small (several 100's J) energy generators of shorter (10's of ns) duration with large (~ 100 Ω) impedance. The use of Tesla transformer by Mesyats *et al* [12], Gubanov *et al.* [13], amongst others, and the semiconductor opening switch by Kotov *et al* [14] are also viable alternatives to the PFN-Marx system for producing short duration pulses.

Acknowledgements

The author is indebted to Dr. A. L. VanKougnett, NRC. Interest shown by Dr. C. Gardner, and Dr. S. Kashyap, DREO is appreciated. PSpice simulations were carried out by Mr. D. Kekez. Technical contributions by Mr. K. Schoenherr, NRC, and by Mr. T. Zandbelt, CRC, are acknowledged. This work was supported in part by DREO.

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