A Compact Modulator for RF Source Development *

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Abstract

A compact, low repetition rate, pulse modulator is being developed for use as a driver in high power microwave experiments. A single stage of the modulator consists of a 16 Ω pulse forming network in a Blumlein configuration driving a 3:1 coaxial ferrite loaded pulse transformer. The output of the transformer is a 100 kV, 150 ns (FWHM) pulse, with a 70 ns flat top ($\pm1.0\%$), into a matched load. A second device, driven with a different pulse line, gives a $130ns$ flat top pulse. To obtain the flat top requires tuning with a reactive circuit in the transformer primary. We plan to stack transformer modules in series to obtain a $500kV$, $1kA$ modulator. A second stage is currently being built and various stacking techniques are being investigated.

I. INTRODUCTION

A compact, pulse modulator is being developed for use in high power laboratory microwave experiments. The goal of the program is to produce a 500 kV, $\sim$ 100 ns pulse operating at ≈ 1 Hz capable of driving a matched 500 Ω load with an efficiency of greater than 50%. A number of designs are being considered for such a modulator [1]. Early work has focused on modulators to be composed of a number of 3:1 coaxial transformer modules driven by Blumlein pulse forming networks. The transformer uses a ferrite loaded coaxial cable geometry, which provides good coupling, and has an adequate voltage standoff to meet the modulator requirements.

The transformer is designed to drive an electron beam in a vacuum diode immersed in an axial magnetic field. We propose to use a ferroelectric cathode as the electron source and experiments are currently in progress to test the emission characteristics of the cathode in high voltage diodes. First results on the emission are reported in the text.

II. BLUMLEIN CHARACTERISTICS

The primary pulse for the modulator is provided by an artificial Blumlein. The Blumlein and a single stage transformer module are shown schematically in fig. 1.

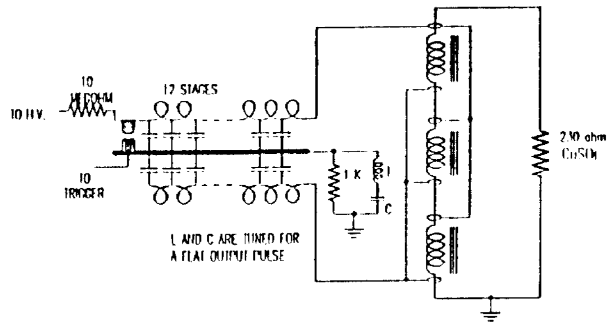

Fig 1. Coaxial pulse transformer module.

Two pulse lines have been used in the present work. The first has a maximum energy storage of 12 J and uses $24, 40$ $kV, 570$ pF capacitors. The inductance per stage is 40 nH and the line impedance nominally 16 Ω. The full width, half maximum pulse duration is 150 ns and the line delivers, when properly tuned a 75 ns flat top pulse into a matched load. The line is mounted inside two cylindrical pipes with the inductor on the axis . This arrangement reduces the effect of the stray capacitance from the inductor to ground. The second line has twelve stages and a stage capacitance and inductance of $3.6nF$ and $350nH$ respectively. The line impedance is 18 Ω with the 250 ns FWHM pulse duration giving a $130ns$ flat top pulse into a matched load. The maximum energy stored in the Blumlein is $54J$ with a capacitor charge of $50kV$. In both cases the center conductor is grounded, the opposite arrangement to that usually employed in Blumlein transmission lines.

III. TRANSFORMER DESIGN

The pulse forming network drives a 3:1 ferrite loaded coaxial cable transformer as shown in Fig 1. The transformer consists of a three turn primary with each turn connected in parallel and a three turn series connected secondary. Each turn is $\sim$ 1.5 m in length and is made of RG-8 cable. The performance of the coaxial cable transformer is strongly affected by the cable capacitance, approximately $150pF$ for each turn. In the three to one step up transformer the voltage across the cable is equal to the load voltage for the second turn and twice the load (charging) voltage for the third turn. The energy required to charge the cables comes from the Blumlein, and the current flow required for the charging makes a significant change in the output voltage. This effect is strongest in

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the case when the transformer is energized by the 12 J Blumlein. The charging current is maximum during the rise and fall times of the output pulse and hence its effects are noted by a second harmonic contribution to the output voltage. To help overcome this effect, and to obtain a flat output voltage pulse, the Blumlein is charged with the center conductor tied to ground through a resistor. In this configuration all three sections of the transformer are initially charged to the Blumlein voltage. On pulsing the transformer the charge stored in the transformer capacitance is redistributed as required by the potential distribution along the length of the transformer. The path for the current flow is through the $1k\Omega$ ground resistor in the Blumlein. The circuit may be tuned to obtain a flat output pulse by adding a series resonant circuit in parallel with the ground resistor as shown in figure 1. The resonant frequency of the circuit is chosen to match the ringing frequency of the charging cable, and for the 12 J Blumlein is about $14MHz$. The second harmonic contribution to the output voltage in the second and 54 J Blumlein is significantly smaller for the same transformer and has not required the tuning used and described above.

Although the stray capacitance effects in the transformer affect the pulse shape strongly, the dominant effect on the transformer performance is set by the ratio of the leakage inductance in the transformer compared to the mutual inductance. To achieve a satisfactory performance requires that the mutual inductance be increased by a ferrite core loading of the cables. This is achieved by adding 114 ferrite rings (id.=1.27 cm, od.=2.54 cm, 1.27 cm thick) onto each length of the coaxial cable. The total Volt-second product of each stage is then increased to about 4.10^{-3} Vs. This provides a large enough flux swing to allow for a $100ns$ pulse at the $40kV$ rated voltage of the 12 J Blumlein. The cores have an initial permeability of about 850, a flux swing of 4300 Gauss, and a maximum permeability of 2500. The core resistivity is about 1.10^8 $\Omega - cm$ allowing for good high frequency operation.

Single transformer modules have been tested on various impedance loads and for excitation with both pulse lines. With the transformer driven by the smaller Blumlein the output pulse into a 500 Ω load is shown in fig. 2. The 100 kV, 150 ns (FWHM) pulse has a 70 ns flat top. The LC tuning has reduced the output voltage ripple to less than 1%. In this figure six shots have been overlaid, illustrating excellent shot-to-shot performance of the module, especially in view of the fact that the switch, a spark gap, was not triggered but allowed to self break. In this example the Blumlein was initially charged to $33kV$. Note that although the transformer gain was 3:1 the load was mismatched and the efficiency was correspondingly lower than the design figure.

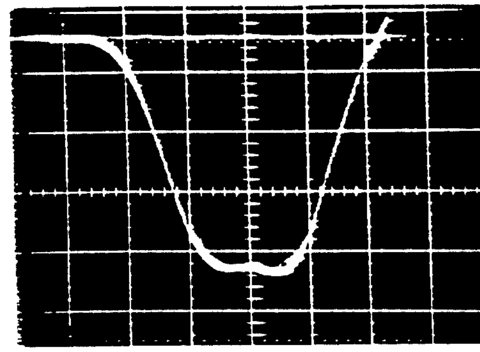

Fig 2. Output pulse from single module of the 12 J system. 23 kV/div, 50ns /div.

When excited by the larger Blumlein the pulse rise time and flat top durations are both increased. The flat top duration now extends to $130ns$ as shown in the overlay of six switch self break discharges. The output pulse into a 500 Ω load is shown in fig. 3. In this case the Blumlein was charged to $12kV$ and the 50 kV, 250 ns (FWHM) output pulse has a 130 ns flat top. The output voltage is about four times the dc charging voltage on the Blumlein, commensurate with the mismatched load. Operation of the system with a 230 Ω load gives the expected three to one step up ratio. For the 12 kV charging voltage the operation into the 500Ω load yields an efficiency of 42%.

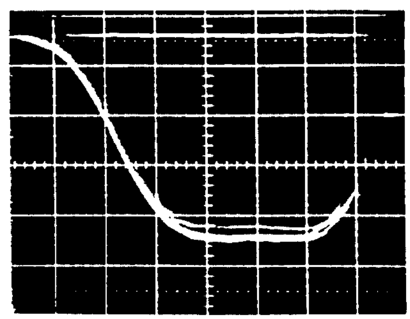

Fig 3. Output pulse from single module of the 54 J system. 12 kV/div, 50ns /div.

IV. ELECTRON BEAM GENERATION

A third transformer system, which uses a four to one step up transformer and gives a $70kV$ output pulse (limited by the volt-second product of the ferrite cores), has been used to test the electron emission from a ferroelectric cathode. This work, which is currently in progress, is being used to obtain data on the suitability of ferroelectric materials as sources for high current ($\sim$ 1 kA) electron beams. In this configuration the ferroelectric cathode is pulsed by a second artificial Blumlein, which is inductively coupled to the ferroelectric through a one to one isolation transformer. Electron emission occurs when the ferroelectric sample (LTZ-2M in these experiments) is pulsed to about $1kV$, with a field gradient of about $10kV/cm$ [2].

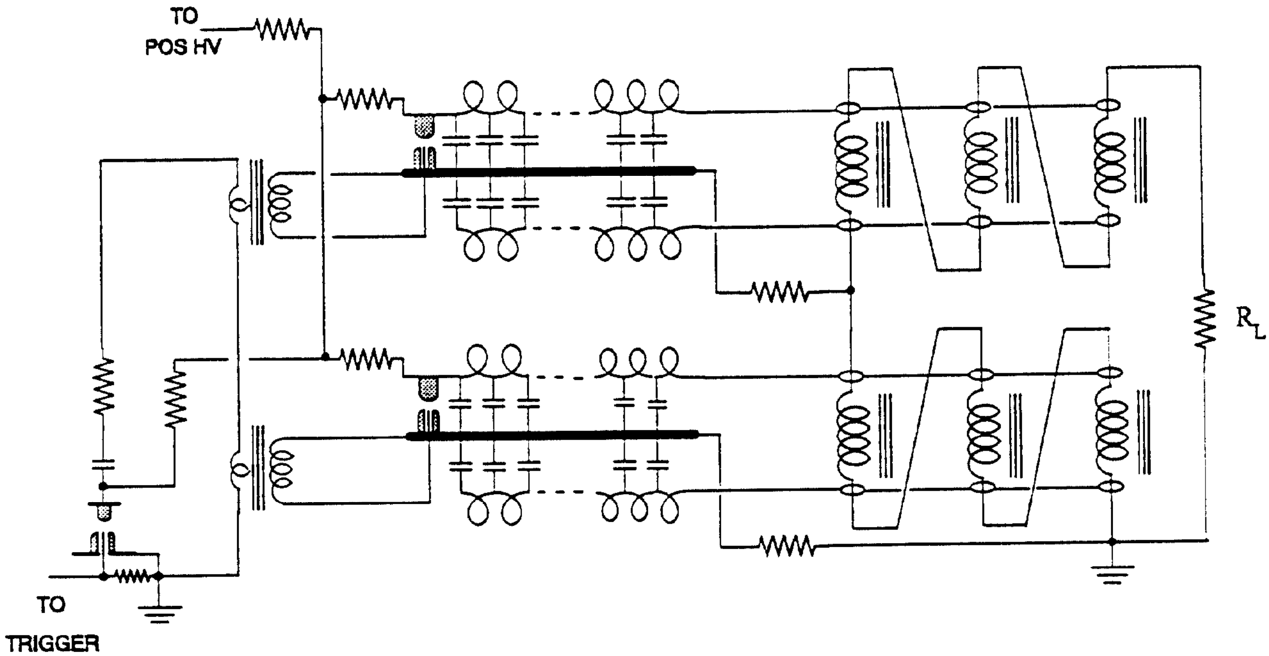

Fig. 4 Schematic of a two Blumlein stacked pulse modulator.

The 70 kV main transformer pulse is applied, in the present configuration, across a planar vacuum diode gap which is typically $3-4$ cm. The electron current through the gap is monitored as a function of the applied voltage. The effect of the time delay between the pulse applied to the ferroelectric (V_{fe}) and the diode gap pulse (V_d) is also measured. Initial results show the following: (i) Diode current pulses up to 200 A, 250 ns have been measured. (ii) If V_d is applied before V_{fe} no significant diode current (I_d) is measured. ($I_d < 10$ A). (iii) If the ferroelectric is replaced with a simple carbon cathode the measured diode current is below the 4 A level set by noise limitations.

These initial results have been limited by the significant shot-to-shot variations in this experiment, and we shall be seeking to improve the performance of this ferroelectric diode in the future. It should be noted that the measured diode current corresponds to an emission current density of 200 A/cm^2 and is about 40 times greater than the emission expected on the basis of the Child-Langmuir law. The diode voltage is limited in the current arrangement to $70kV$, with a $130ns$ flat top output pulse. We are also working on the construction of a transformer with a larger volt-sec product to allow operation of the module up to its design value of $150kV$.

V. TRANSFORMER MODULE STACKING

In order to achieve the required output parameters of $\sim$ $500kV$ and $1kA$ requires that two or three transformer modules be stacked in series. We accomplished this experimentally some time ago [3] with each transmission line being set as an element in a Marx generator. We plan to attempt stacking initially with the arrangement shown in fig. 4. In this case the energy required to float the successive Blumleins comes from the lines themselves. The separate sections will be switched inductively as shown in the figure. This arrangement is currently in satisfactory use for the triggering of the ferroelectric cathode as described above. The transformer modules will be fabricated on RG-218 cable to allow for the greater voltage hold off required in the second stage (or third, if needed).

To complete our design program we have in progress work on stacking of multiple transformer stages and also on extending the flat top width of the voltage output pulses.

VI. REFERENCES

[1] Pulse Generators, Ed. G. Glasoe and J. Lebacqz, MIT Radiation Series, M^{c}Graw Hill 1948.

[2] J. D. Ivers, L. Schächter, J. A. Nation, G S. Kerslick, and R. Advani, *J. Appl. Phys.*, **73**, 2667, (1993).

[3] J. D. Ivers, and J.A. Nation, *Rev. Sci. Instrum.*, **54**, 1509, (1983).