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ABSTRACT

Methods of producing square and sine wave beam modulation of a 3 MeV Van de Graaff accelerator are described.

Square pulses are produced at frequencies from 100kc/s to d.c. with up to a 100 per cent duty cycle and a minimum pulse length of 8 μs. The ratio of the off-current level to the on-current level is less than 5×10^{-4} and can be further reduced by a post-acceleration deflection system to less than 10^{-5}. The unit, which is triggered from a command pulse external to the machine, is in the top terminal of the Van de Graaff and has shown itself to be highly reliable over some 1,000 hours of machine operation.

The sine wave modulation unit described here operates in the range 80-1000 c/s with a modulation depth of up to 90 per cent and higher harmonic contamination of less than 1 per cent.

Note: This work has been submitted to a journal. Further details can be obtained from the author or from the Director of the Research Establishment.

CONTENTS

1. INTRODUCTION

Pulsed neutron source techniques have become a powerful tool in many fields in reactor physics. In general the pulsed waveform is either square or sinusoidal although Arai and Küchle (1965) have reported an experiment in which an effectively exponential waveform was used. The square pulse is used typically in die-away experiments on both pure moderators and fuelled systems (Beckurts 1965, Keepin 1964), in pseudo-random pulsed experiments (Uhrig 1965) and in neutron history experiments (Barnard et al. 1963). So far the sine wave pulses have been used only in the analogue of the die-away experiment (Perez and Uhrig 1963).

The die-away experiment places the most stringent conditions on the neutron source. Provided sufficient intensity is available any pulsed neutron source suitable for a die-away experiment can be used in the other experiments. A pulsed neutron source suitable for a die-away experiment should have the following properties:

1. The 'off' pulse current level should be small compared to the 'on' pulse current level. A reasonable figure is a ratio of 10^{-5}.
2. The pulse length and repetition times should be variable over a wide range to match the decay constants of the assemblies under study. For example, in water systems, pulse lengths of from 100-500 μs may be required, with the time between pulses in the range 500-5,000 μs; in BeO or graphite systems the pulse lengths would be 500 μs - 5 ms with the time between pulses in the range 5-20 ms.
3. The source should be externally triggered so that it can be driven by some master timing system used to drive the other timing equipment.
4. The rise and fall times of the pulse do not seem critical but it appears preferable to keep them in the 1-10 μs region.
5. The source should be highly reliable.
6. The intensity should be controllable.

The source intensity required will depend very much on the experiments being done, but a source strength of 10^{12} - 10^{13} n/sec is sufficient for a wide range of experiments, excluding the neutron history type of experiment.

Criteria for a sine wave neutron source have received little comment in the literature. Calculations at this laboratory have shown that the following properties would be useful:

1. The modulation depth should be greater than about 90 per cent so that the ratio of the sine wave component to the d.c. level is maximised.
2. Harmonic distortion should be less than 5 per cent, especially at low frequencies.
3. The a.c. component of the source should be a maximum at the higher frequencies, as it is rapidly attenuated and quickly disappears into the d.c. 'background'.
4. The frequency range should be at least 0-10 kc/s and preferably 0-100 kc/s to cover the thermalization region.

Section 2 of the paper describes the method and equipment used to produce a square wave modulated beam from a 3 MeV Van de Graaff accelerator and describes the performance of the equipment over several hundred hours of machine operation. Section 3 describes the method used to produce a sine wave modulated beam from the accelerator and also gives some performance figures.

2. SQUARE WAVE MODULATION

2.1 Method of Operation

The 3 MeV Van de Graaff has, as part of its standard equipment a deflection chamber in the top terminal, composed of deflection plates, aperture and suitable focus electrodes, (H.V.E.C. part number D-K-TU-35). It is designed to produce pulses in the range 10-100 ns. This deflection chamber has been used to produce a square wave pulsed beam by applying a suitable voltage pulse to one of the lower deflection plates. The deflection voltage can be triggered on and off by command pulses fed through the light pipe system, indicated in the block diagram of Figure 1 and described in more detail below. The changeover from nanosecond operation to square wave operation is effected by a switch at the control desk of the machine.

It requires about 40 volts or so, applied between the bottom plates in the deflection chamber to move the core of the beam (which at that stage has an energy of some 30 keV) away from the aperture. However, because of the penumbra round the beam, a deflection voltage of about 1 kV is used to minimize the current escaping into the accelerator tube during the off-current period. The 1 kV is applied through a suitable resistor chain to one of the deflector plates. The deflection plate is in parallel with a valve (V8 of Figure 2) which acts effectivel as a switch. The valve is normally biased beyond cut-off but when a positive voltage (~200V) is applied to its grid it conducts heavily and the voltage on its anode approaches that of the cathode. The cathode is connected to the zero-voltage line of the top terminal and hence the voltage at the deflection plate swings between about 1 kV and zero. In practice the voltage on the anode does not go to zero when the valve is biased on, but remains some 12 volts positive. To overcome this, a variable bias voltage covering the range -40 to +20 volts is applied to the other deflection plate to ensure zero voltage difference between the deflection plates during the on-current period.

The design is fairly conventional and the circuit details are shown in Figure 3. The emphasis has been placed on reliability and ruggedness. The system consists of an 'on' channel and an 'off' channel which have identical circuits and whose outputs feed into a flip-flop (V6 and V7) which supplies the drive pulse for the final output valve V8. In each of the channels, the incoming trigger pulse is amplified (V1, V9) and fed through diodes (V2, V10) which are biased to prevent pulses smaller than 5 volts passing through the system and producing accidental triggering of the deflection voltage. The outputs from V2 and V10 drive monostables (V3, V4, V11, V12) which shape the amplified pulses to pulses about 10 μs long with fast (~ 1 μs) leading and trailing edges. These pulses are again fed through biased diodes to discriminate against spurious pulses before passing on to the flip-flop.

The circuitry used to provide the light flashes which trigger the 1 kV pulse generator is shown in Figure 3. The light flashes are obtained from pulsed indicator lamps with a fluorescent anode (DM160). The unit can operate in two modes. In one mode, an 'on' command pulse is fed directly to the grid of the DM160 in the 'on' channel and the 'off' pulse to the DM160 in the 'off' channel. The time between the two pulses determines the beam pulse length from the machine. In the second mode, the front edge of a command pulse is fed to the grid of the 'on' DM160. The back edge of the command pulse triggers a tunnel diode-transistor hybrid circuit (TD1, TR1) which triggers a monostable (TR2, TR3) to drive the 'off' DM160. Hence in this mode the beam pulse length is determined by the length of the input command pulse.

2.2 Performance of the Square Wave Pulsing

The square wave pulsing unit described above has been installed for some 1,000 hours of machine time. During this time it has operated for some 430 hours and the only major problem has been a reduction of light transmission caused by the formation of colour centres in one of the Perspex light pipes. The affected light pipe is very close to the X-ray source formed by back-streaming electrons at the top of the accelerator tube. The discoloration causes an attenuation of the light signal that increases with time until the photomultiplier output is not high enough to pass through the discriminator diodes.

It should be noted that the environmental conditions in the top terminal are quite severe. Accelerations due to vibration reach a maximum of 5G at 600 and 1200 c/s and necessitate the use of anti-vibration mountings to avoid undue stresses on some of the more sensitive components. Voltage breakdowns in the accelerator tube induce high voltage surges in the circuitry of the top terminal which rapidly destroy any solid state devices. For this reason hard valve circuitry was used throughout to improve the reliability of the system. Finally the pressure in the top terminal is 280 p.s.i. with temperatures up to 80°C and special components are required.

The current wave form obtained from the machine when it is producing square pulses is shown in Figure 4. It can be seen that the rise and fall times are fairly fast (~ 1 μs). However, details of the leading and trailing edges shown in Figure 4 indicate that there is a delay of about 2 μs after the command trigger pulse before the beam starts to move. The staircase effect on the trailing edge of the pulse is thought to be caused by the penumbra round the beam. The dip near the front edge is not well understood, but does depend critically on the gas pressure in the ion source and also on the focusing in the deflection chamber.

The maximum current available in the pulse is 1.3 mA of protons and 850 μA of deuterons, both limits being set by the ion source. The majority of the work done using the square wave pulsing has used deuterons with 300-750 μA in the pulse. The off-pulse current level, even with a 1 kV deflection voltage, is about 0.05 per cent of the on-pulse current level. Hence for the neutron die-away experiment it has been necessary to install a 10 kV post-acceleration deflection unit (Figure 5) which is activated by the same pulse that triggers the beam pulse. This unit reduces the ratio of the off-pulse current level to on-pulse current level to less than 10^{-5}.

The top terminal pulsing unit is capable of a 100 per cent duty cycle, so that it is possible to run the beam continuously, switching off at a given signal, or conversely to have no beam, then trigger it on. The minimum pulse length available is 8 μs measured as the full width at half maximum.

3. SINE WAVE MODULATION

3.1 Method of Operation

If the centre of a circular beam is moved with simple harmonic motion from the centre of an aperture of the same diameter, to a distance of one radius length from the edge of the aperture, the variation of beam intensity at a target placed after the aperture is given by

$$I = A(\Pi/2-\sin^{-1}\tfrac{1}{2}(1-\sin\omega t) - \tfrac{1}{2}(1-\sin\omega t)\ (1-\tfrac{1}{4}(1-\sin\omega t)^{2})^{\frac{1}{2}}) \qquad \ldots(3.1.1)$$

Fourier analysis of this expression indicates that it can be described to within 20 per cent by the form:

$$I = A(1 + \cos\omega t)$$

The higher harmonics present in the expression (3.1.1) can be suppressed by feeding a signal from the target at which sine wave modulation is required, into a suitable feedback system. Such a feedback system is indicated in the block diagram of Figure 6 and the circuit details are given in Figure 7. It is designed for a loop gain G of 50 at low frequencies falling to 14 at 1.5 kc/s. The feedback system reduces any distortion in the signal by the factor 1/(1 + G).

The whole system does not have to be too rugged as it is outside the pressure tank and not exposed to the rather extreme environment of the top terminal. The aperture becomes a source of neutrons if deuterons are used in the beam. However, the neutron radiation from the aperture is small compared to the output from the target. It could be further reduced if the deflection unit were installed in the top terminal but there would be problems with the frequency response of the feedback loop.

3.2 Performance of the Sine Wave Modulation

Figure 8 shows a frequency analysis of a modulated beam with and without feedback, when the input frequency is 490 c/s. The signals at 50,100,150 and 200 c/s are produced by the mains supply at 50 c/s. Those at 345 and 690 are the fundamental and higher harmonics of the alternator in the top terminal of the machine, while those at 490, 980 and 1,470 are the input signal and its harmonics. The feedback reduces all the 'unwanted' frequencies quite dramatically, the harmonics of the input signal falling to less than 1 per cent.

The modulation depth during these runs is about 90 per cent, it being difficult to reduce the beam intensity completely to zero and still maintain good control of the frequency. The device described above covers the range 80-1,000 c/s.

A new system has been designed for 0-10 kc/s operation.

4. DISCUSSION

The square wave pulsing unit described above has been installed in a 3 MeV Van de Graaff already equipped to produce 10 ns pulses at a 1 Mc/s repetition rate. Thus, by the use of suitable controls at the console the one machine can produce pulses from 10 ns wide to d.c. with repetition rates from 0-1 Mc/s with a small gap at repetition frequencies in the range 1 Mc/s - 100 kc/s. The peak current available in the pulse is about 1 mA. This implies a source intensity of 2×10^{12} n/sec if the $Be^9(d,n)B^{10}$ reaction is used at 3 MeV.

The square pulse, with the addition of post-acceleration deflection, satisfies the criteria set out in Section 1 and has proved suitable for the die-away type of experiment. The low background level present during the off-current period, and the intense initial neutron pulse make it possible to follow the decay of neutron population for a long time. The ability to trigger the beam pulse externally also makes the source eminently suitable for the pseudo-random pulsing type of experiment. Moreover, this triggering facility would prove useful in an experiment where events may be few and where background from the Van de Graaf beam may be a problem. In this case it is possible to run the machine at a high d.c. level until an event of interest occurs, at which time a pulse from a suitable counter will cut the beam off.

The sine wave modulation unit satisfies all the criteria of Section 1 except that of wide frequency range. A circuit has been designed to cover the wider frequency range.

It should be noted that the sine wave pulsing unit is basically a feedback system or 'follower' and therefore is capable of producing any wave form compatible with its frequency response by substituting the desired wave form for the sine wave at the input of the differential amplifier.

5. ACKNOWLEDGEMENTS

We would like to thank Mr. W. O. Hill of General Nucleonics Division of this establishment for his help in building the equipment, and also the operators of the 3 MeV Van de Graaff of Physics Division, who helped overcome some of the initial troubles. We would also like to thank Dr. J. R. Bird for some stimulating discussions.

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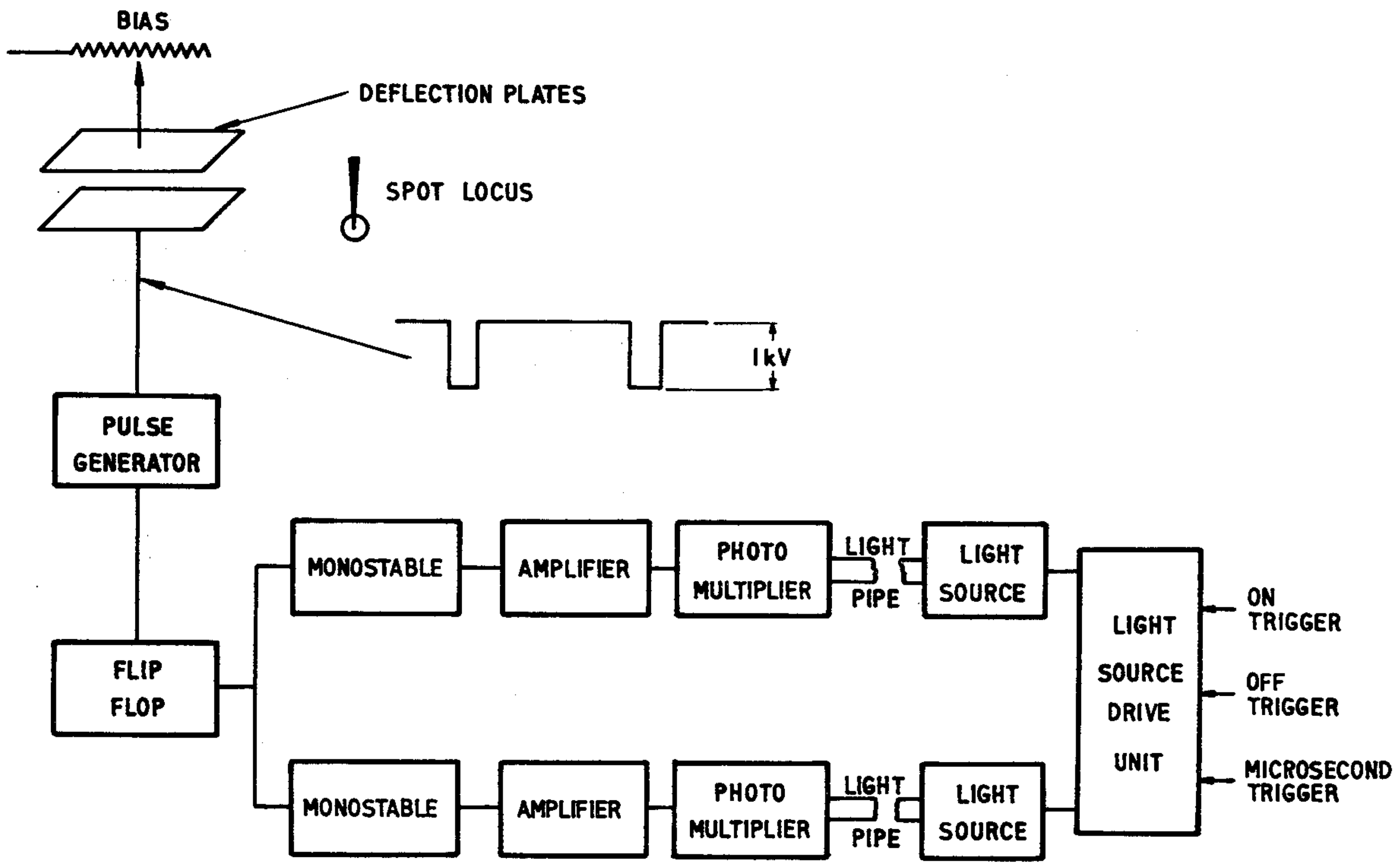


FIGURE 1. BLOCK DIAGRAM OF SQUARE WAVE PULSING SYSTEM

P1171

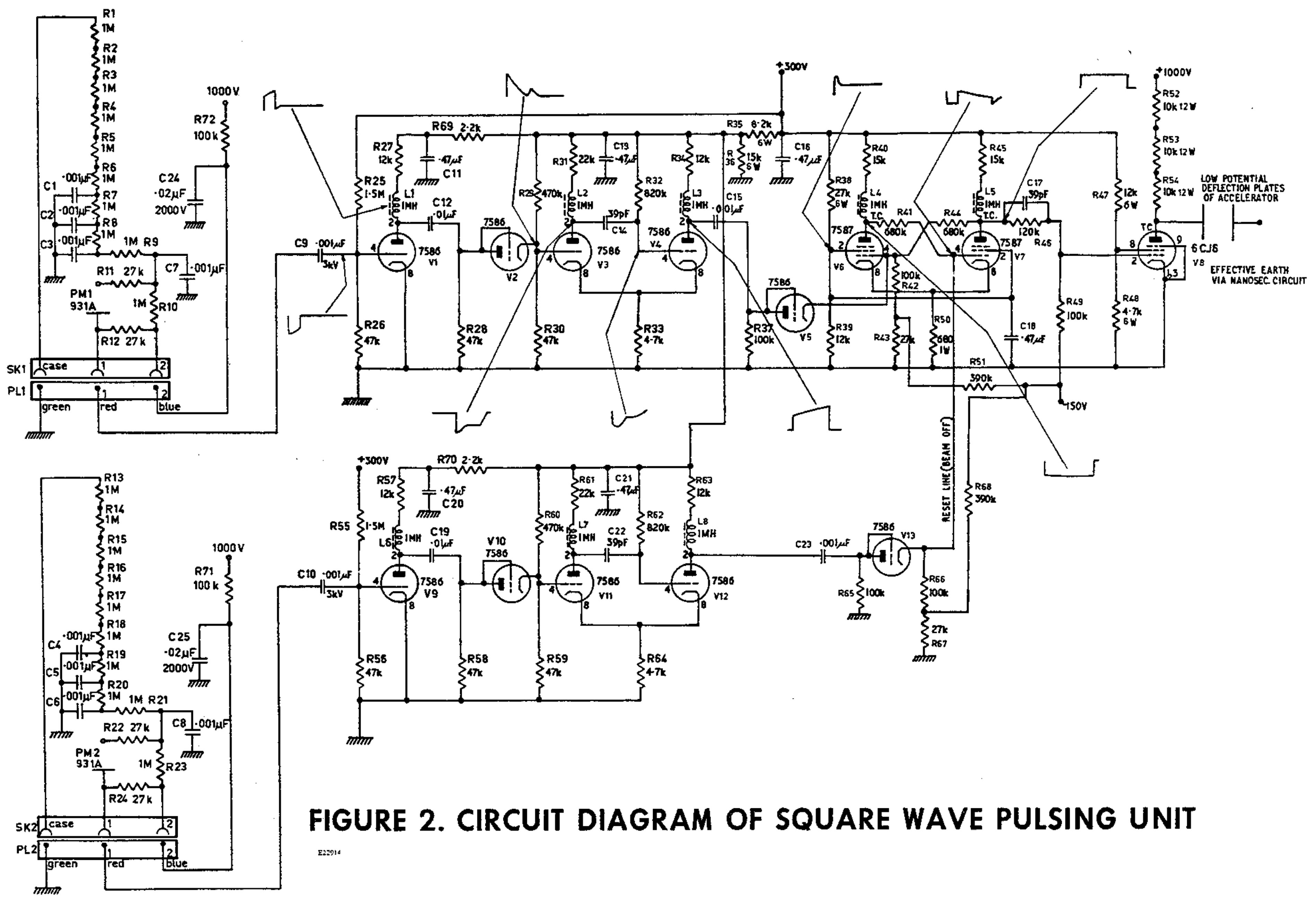


FIGURE 2. CIRCUIT DIAGRAM OF SQUARE WAVE PULSING UNIT

E22014

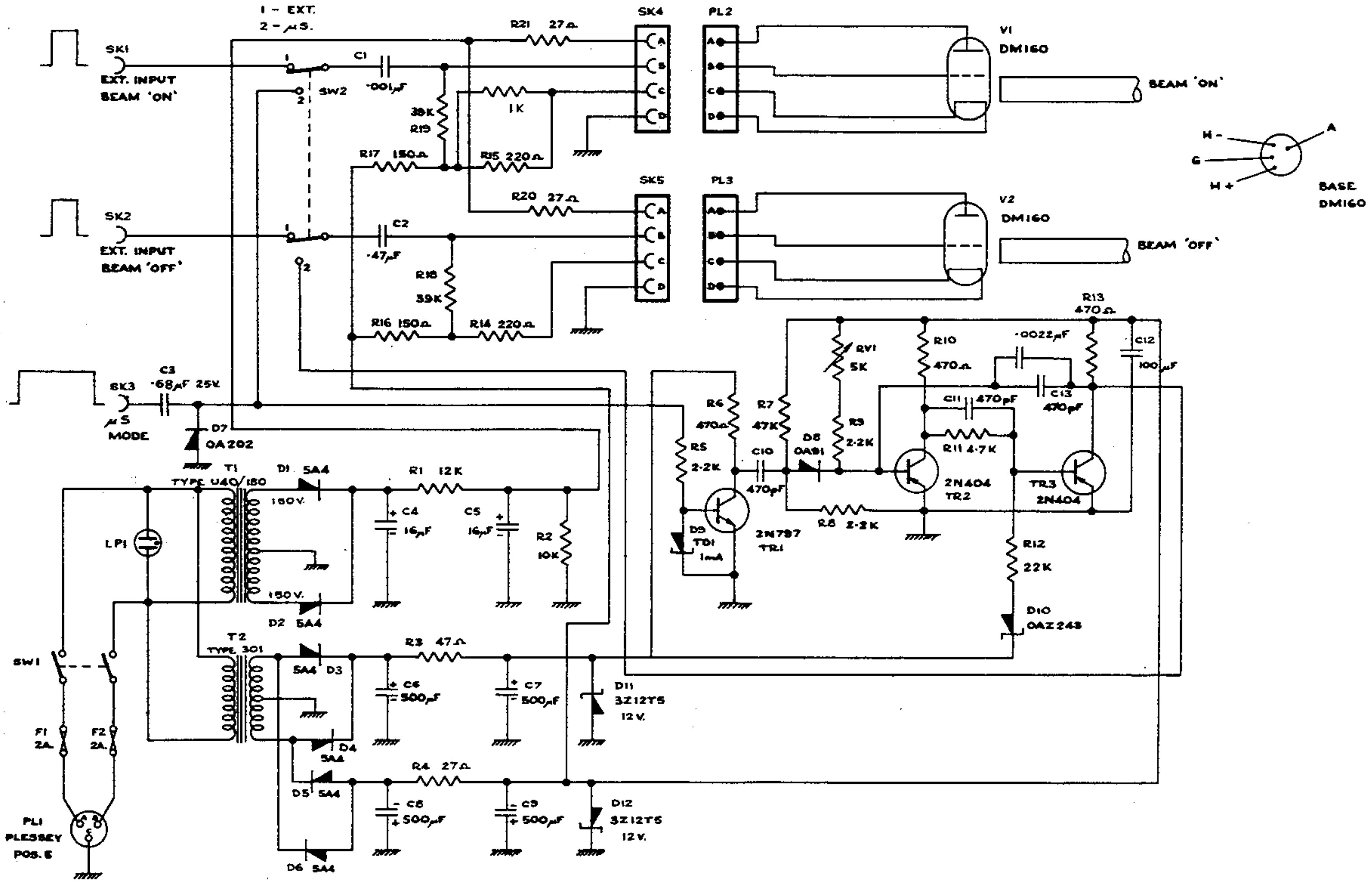
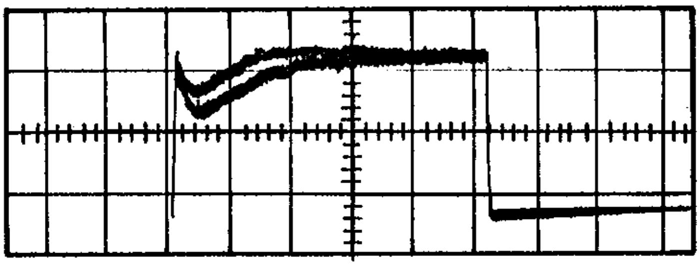
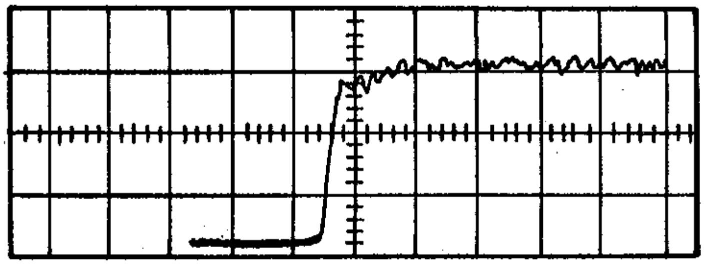


FIGURE 3. CIRCUIT DIAGRAM OF LIGHT PULSING UNIT

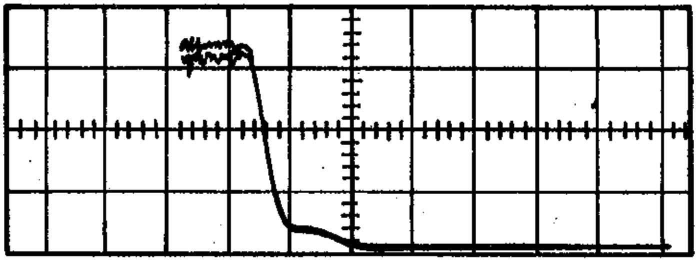
E23796



(A) Beam pulse; 700µA in peak (100µs/cm)



(B) Leading edge; triggered from start pulse (1µs/cm)



(C) Trailing edge; triggered from stop pulse (1µs/cm)

FIGURE 4. WAVEFORM OF SQUARE WAVE MODULATION

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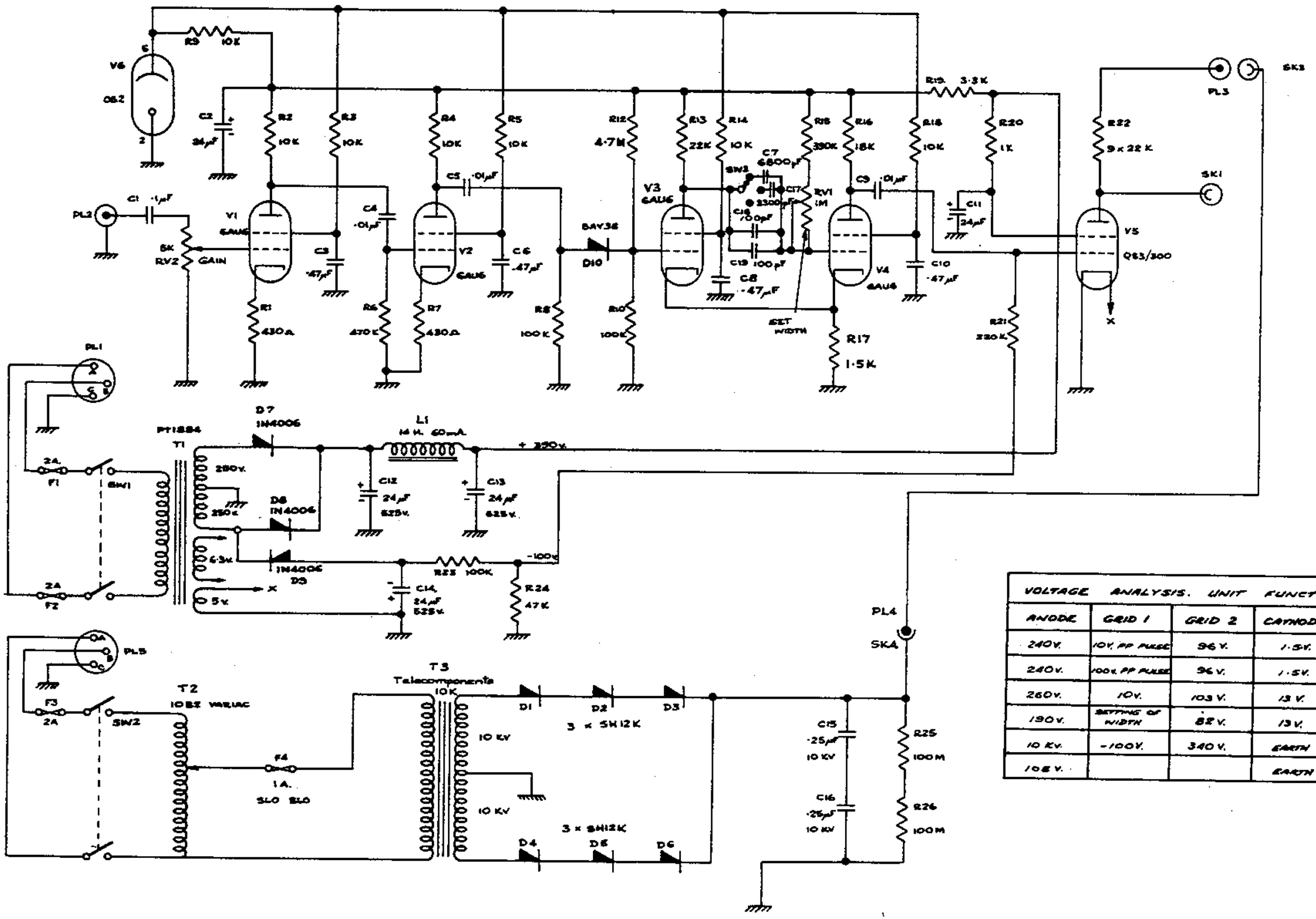

VOLTAGE ANALYSIS. UNIT FUNCTIONING.

ANODE	GRID 1	GRID 2	CATHODE	VALVE N°
240V.	10V. PP PULSE	96 V.	1·5V.	1
240V.	100V. PP PULSE	96 V.	1·5V.	2
260V.	10V.	103 V.	13 V.	3
190 V.	SETTING OF WIDTH	82 V.	13 V.	4
10 KV.	-100V.	340 V.	EARTH	5
108 V.			EARTH	6

FIGURE 5. CIRCUIT DIAGRAM OF POST-ACCELERATION DEFLECTION UNIT

E21301

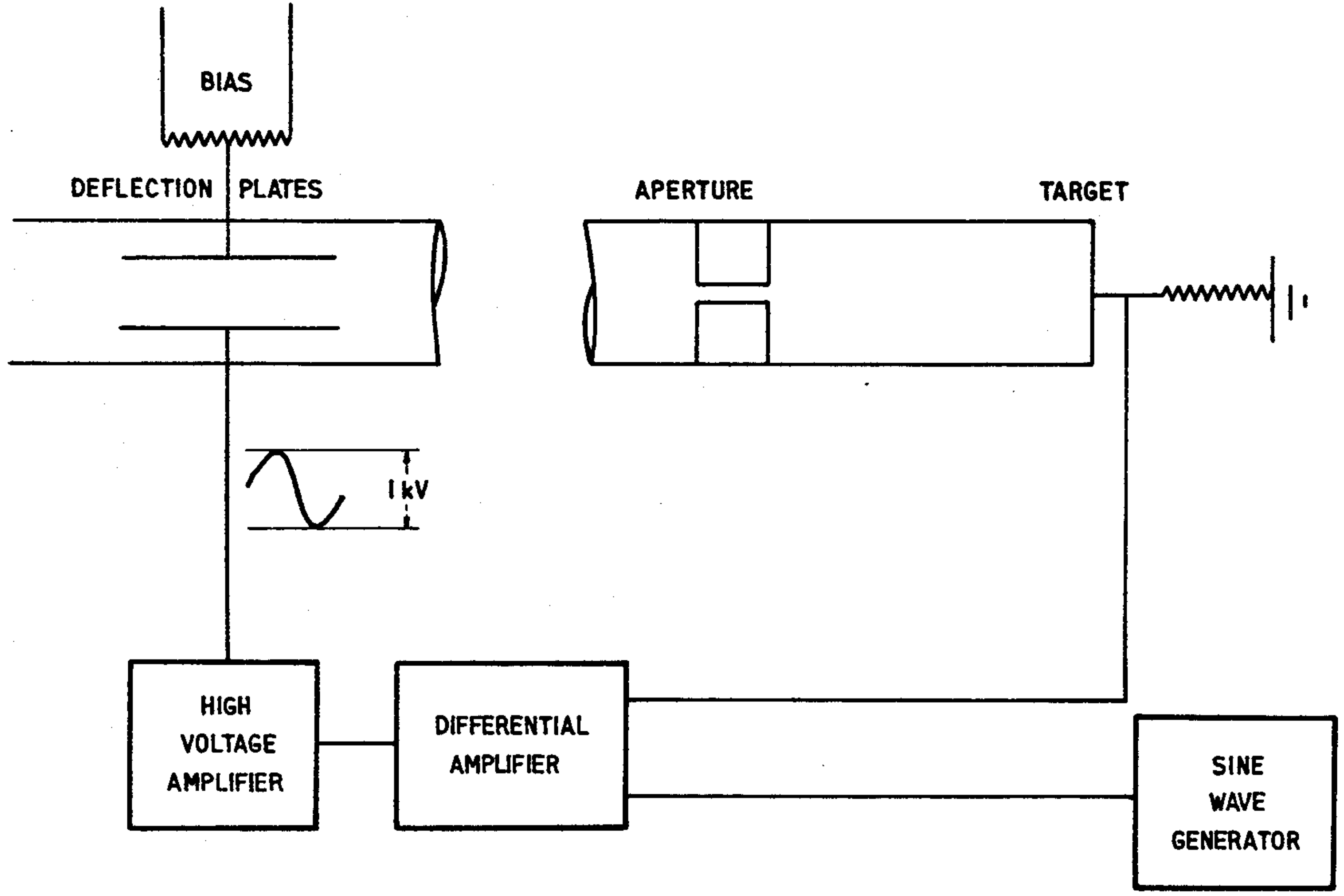

FIGURE 6. BLOCK DIAGRAM OF SINE WAVE MODULATION UNIT

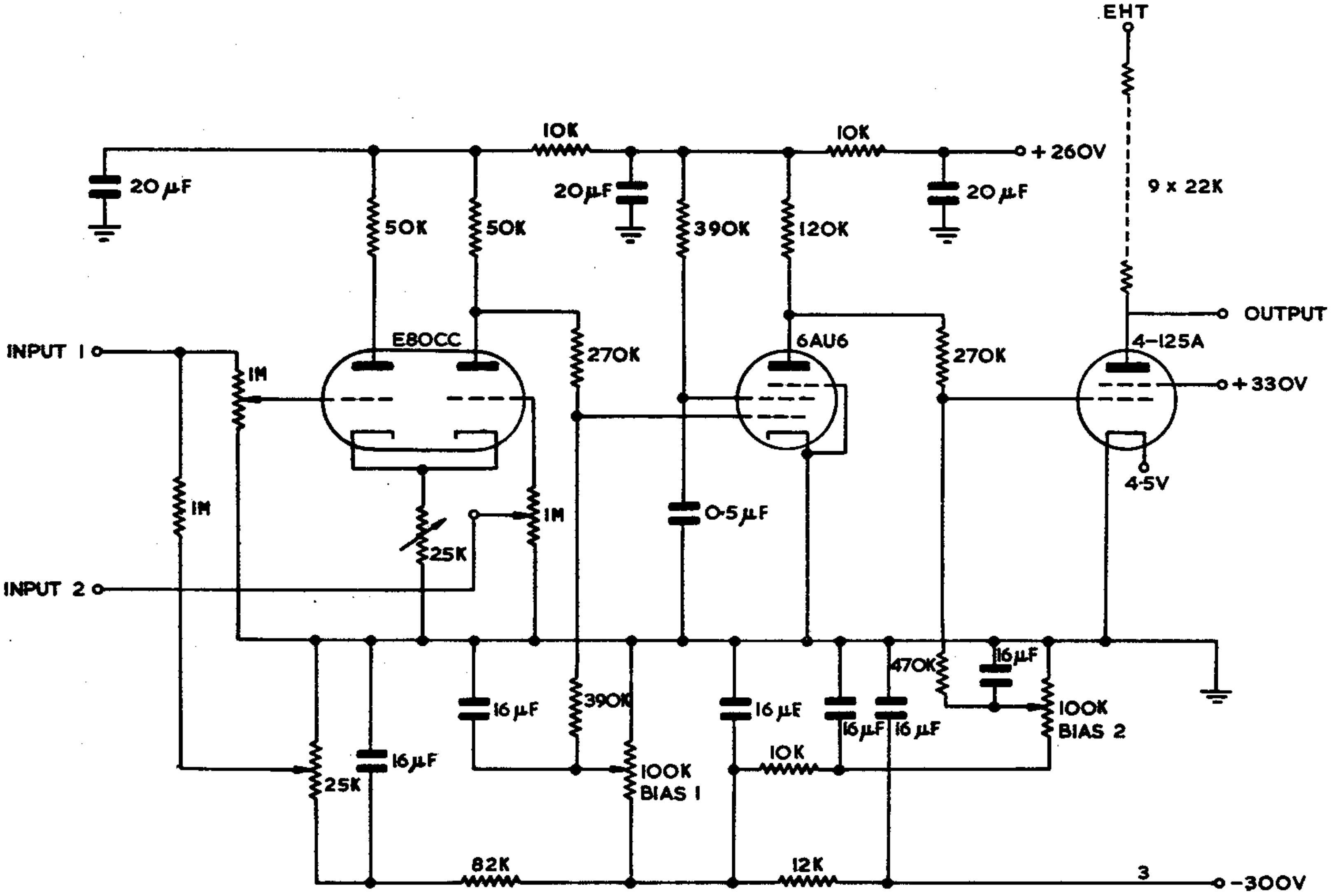

FIGURE 7. CIRCUIT DIAGRAM OF SINE WAVE MODULATION UNIT

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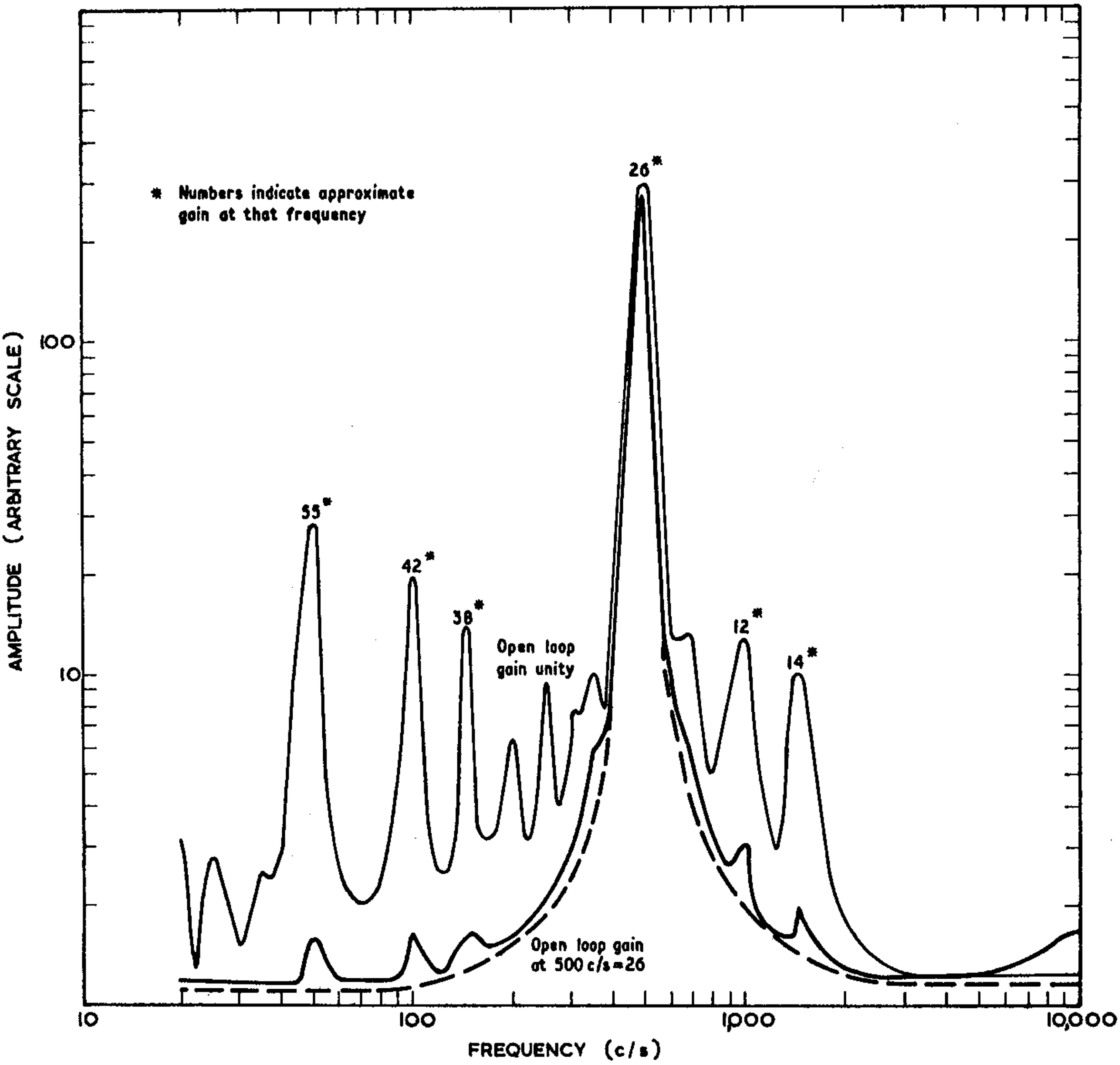

FIGURE 8. FREQUENCY ANALYSIS OF SINE WAVE MODULATED BEAM

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