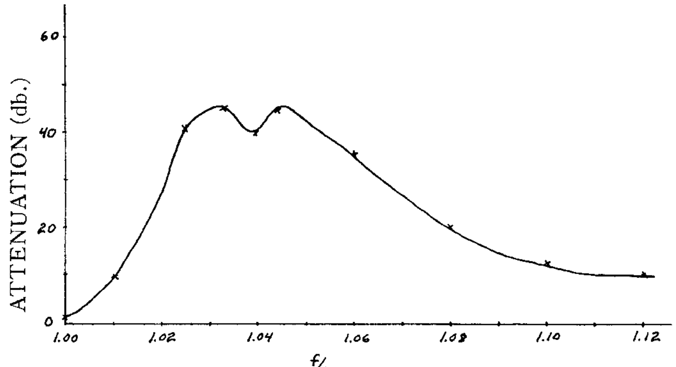

Fig. 13—Attenuation of a magic-tee cutoff filter.

The attenuation vs frequency characteristic of this filter is given in Fig. 13. To obtain greater rejection in the stop band, two or more filters can be cascaded. Another method is to employ a double magic tee; *i.e.*, one with two E arms and two H arms.

Conclusions

Two band-rejection filters employing the waveguide cutoff effect have been discussed. They are the E plane tee cutoff filter and the magic-tee cutoff filter. By appropriate matching techniques, E plane tee cutoff filters have been designed with a vswr of less than 1.5 over 8, 10, and 16 per cent pass bands while maintaining greater than 25 db rejection over 8, 10, and 6 per cent bands, respectively. A magic-tee cutoff filter has also been constructed which has a vswr of less than 1.7 over a 20 per cent frequency band. By proper design of the shorted E and H arms, greater than 10 db rejection has been obtained over a 12 per cent band.

Acknowledgment

The author wishes to acknowledge the assistance of Mr. G. C. Shaw in formulating some of the ideas presented here. He also wishes to express his gratitude to Dr. Ernest Wantuch and Mr. T. S. Saad for their suggestions.

Technique of Pulsing Low Power Reflex Klystrons

J. I. DAVIS†

Summary—**Very little published information is available on pulsing low power reflex klystrons. Since low power reflex klystrons have been generally designed for cw operation as local oscillators, a minimum of effort has been directed toward the development of specific low power pulse reflex klystrons.**

This paper summarizes an effort that has been directed toward pulsing typical low power reflex klystron with a description of the techniques evolved and a summary of the limitations and merits of each technique. Included also is a description of a pulse klystron "priming" technique that minimizes the effects of pulse shortening and leading edge jitter associated with typical pulse operation.

Introduction

It HAS BEEN apparent for some time to designers of microwave equipment that there has been little or no attempt by the klystron tube manufacturers to design low power klystrons for pulse application. In general, the low power klystrons have been designed for local oscillator use in radar and beacon receivers, and in equipment such as spectrum analyzers. A great deal of effort of late has been devoted toward pulsing high power klystrons for use in generating high speed particles and for use in large anti-jamming radar systems. This has forced the designers of low power beacons and rf signal generators to rely almost wholly on their wit and ingenuity to find suitable techniques for pulsing low power klystrons for optimum pulse fidelity and minimum pulse jitter. In addition to the lack of information from manufacturers on pulsing klystrons there has been very little written in the literature on suitable techniques for pulsing klystrons to yield minimum leading edge jitter and pulse shortening.

Because many of the new guided missile systems have stringent requirements for rf pulsed coded modulation to meet their tactical requirements, a great deal of effort has been expended in advancing the state of the art of pulse circuit design. The circuitry itself has preceded the pulsed rf techniques primarily because of the availability of new components to the circuit designer. These components consist essentially of improved pulse transformers, more reliable thyratrons, and improved hard tube modulator tubes. The basic difficulty of reliable pulsed rf systems has been associated primarily with the pulsing of the klystron itself.

Starting of Pulse Reflex Klystron

It is well known that all electronic oscillators are started by noise or circuit transients associated with the oscillator. This concept applies equally well to the starting of reflex klystron oscillators. However, when one is concerned with pulse operation of reflex klystrons there exists the distinct possibility that the oscillation could have been started by shock excitation of the resonant cavity by the pulsed beam current.

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It will be shown that the initial excitation produced by shot noise in the beam exceeds that induced by the current transient by a very large factor. Had it been found that the microwave voltage produced by the high-frequency components of the pulse was larger than the voltage produced by shot noise, the voltage produced by the pulse would always have been the same and there would have been no evidence of leading edge jitter associated with the rf pulse. This, of course, is not the case and accounts for typical rf pulse leading edge jitter.

The relative effects of Johnson noise and shot noise in building up oscillation can be expressed by the following ratio:[1]

$$\frac{Is^2}{It^2} = \frac{eI_o}{kTG} = \frac{11{,}600 I_0}{TG};$$

where

I_s = shot noise current,
I_t = Johnson noise current,
I_0 = gap current,
k = Boltzmann's constant 1.374×10–23 Joule per °K,
e = charge of an electron 1.59×10–19 coulombs,
G = conductance defined as M/Q,
M = admittance of mode,
Q = loaded Q of klystron cavity.

For a typical klystron such as a V-153 operating at 9,500 mc with a beam voltage of 300 volts, and operating in the $4\frac{3}{4}$ mode the following values can be approximated:[2]

$$T = 293°K\ (20°\text{C})$$
$$I_0 = 8.8 \times 10^{-3} \text{ amperes}$$
$$M = 2.22 \times 10^{-4} \text{ mhos}$$
$$Q = 150$$

then

$$\frac{I_s^2}{I_t^2} = 1.57 \times 10^3.$$

From this ratio it becomes evident that the shot noise is of greater magnitude and importance than Johnson noise in the tube.

To proceed further, it is now desirable to compute the relative effects of shot noise compared with high-frequency transients induced by the applied video pulse, in starting klystron oscillations. This can be expressed by the following ratio:[1]

$$\frac{Vs^2}{V^2} = \frac{eQ\Delta t^2 \omega_0^3}{2I_0};$$

where

V_s = shot noise voltage,
V = transient voltage,
$\omega_0 = 2\pi \times$ (klystron frequency),
Δ_t = rf pulse build-up time.

Assuming the following approximate values for the V-153 Klystron:

$$I_0 = 8.8 \times 10^{-3} \text{ amperes},$$
$$Q = 150,$$
$$\Delta t = 2 \times 10^{-8} \text{ seconds},$$
$$\omega_0 = 5.96 \times 10^{10} \text{ radians per second},$$

then

$$\frac{V_s^2}{V^2} = 115.$$

This ratio points out clearly that the oscillations are built up from shot noise rather than from high-frequency transients induced by the pulse.

Practical Applications and Considerations

Experience has indicated that the application of a video modulation pulse to one klystron will not, of necessity, yield the same detected rf video pulse when applied to another type of klystron. As an example, the V-260 and V-280 klystrons were pulsed with the same circuit techniques. The detected video pulses were significantly different, the leading edge jitter also differed, and the spectrums as noted on a spectrum analyzer were noticeably different. In discussion of this problem with the klystron manufacturer it was indicated that both klystrons operated satisfactorily as local oscillators, the function for which they were designed and tested, and that the results of pulsing these klystrons would be of great interest to them. They suggested that further laboratory tests would probably yield optimum repeller modes for best pulse operation of each klystron. It was also pointed out that there may exist an optimum direction for pulsing into a klystron mode; that is to say, the pulse spectrum may be noticeably different when the klystron is pulsed from a high static repeller voltage into a particular mode rather than from lower static repeller voltage into the same mode. Tests indicated in this regard that there was no noticeable difference when this was tried on the $4\frac{3}{4}$ and $5\frac{3}{4}$ modes of the klystron under test.

It might be pointed out that:[3]

1) That a klystron would have the best starting time characteristics if it were operated in a mode associated with the longest drift time in the drift space;
2) That the operating characteristics would be a function of external circuit loading;
3) That the rise time of the applied pulse and klystron Q were important considerations;

[1] Bell Tel. Labs. Staff, "Radar Systems and Components," D. Van Nostrand Co., Inc., New York, N. Y., pp. 702–705; 1949.
[2] Approximate values as furnished by Mr. Arnold Acker of Varian Associates.

[3] Bell Labs. Staff, *op. cit.*, p. 498.

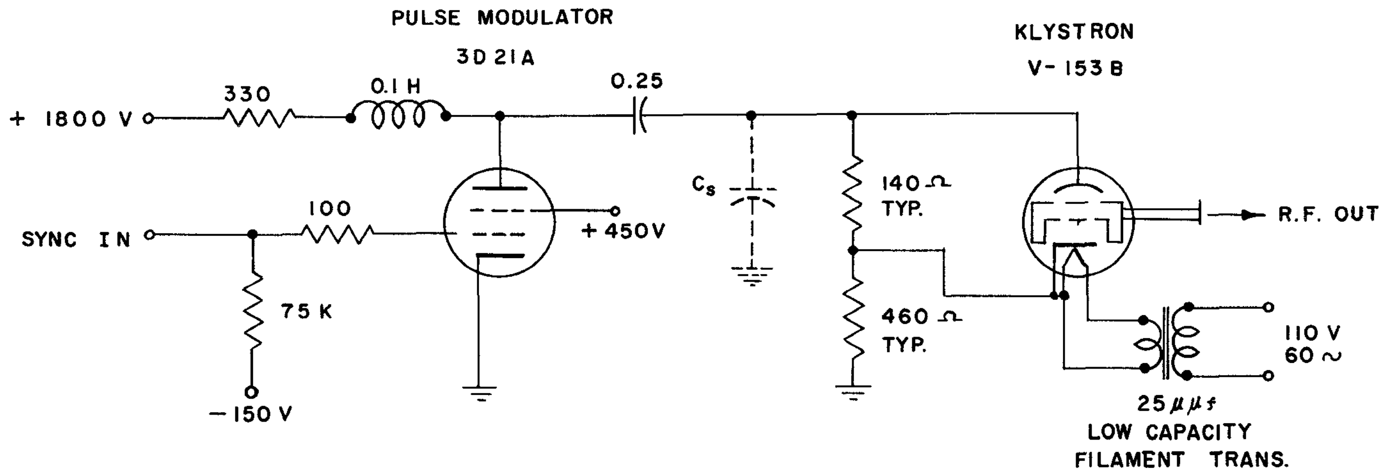

Fig. 1—Klystron beam and repeller pulsing.

4) The general klystron operation is a direct function of the basic electron optics design.

With the above considerations noted, concerted effort was directed towards determining the best technique for pulsing klystrons so as to yield best pulse modulation operation. Basically, three pulse techniques were explored:

1) Pulsing the the beam voltage only.
2) Pulsing the repeller voltage only.
3) Pulsing repeller and beam voltage simultaneously.

The results follow.

Simultaneous Beam and Repeller Pulsing

Pulsing both elements simultaneously appeared to give the poorest results. The results were interpreted by observing the detected rf video rectangular pulse as well as comparing the observed spectrum on a spectrum analyzer for theoretical $(\sin X/X)^2$ distribution of energy. It was interesting to note that the detected video pulse was quite misleading, for it looked to the uncritical eye very much like the applied video pulse. Closer observation, however, indicated pulse shortening, leading edge jitter, and poor rise time.

The spectrum consisted essentially of almost random spectrum lines with no definite nulls, symmetry or pattern. It is quite possible that the circuitry employed (Fig. 1) to pulse simultaneously both the repeller and beam elements of the klystron, in this case the V-280, could have been optimized and perhaps yielded better results. It was taken as a good engineering guess, however, that since the same circuitry was used in pulsing elements of the klystron with better results, improving the basic pulse circuitry would not, in itself, significantly improve the spectrum.

It was concluded from empirical observations with consideration of the electrical characteristics of klystrons, that it would be most difficult to pulse simultaneously the repeller element, which is a high impedance element, and the beam element (or cathode), which is a relatively low impedance element, and expect both elements to have the same volts per unit time, change in potential with identically applied pulses. To enlarge upon this point, we might add that it would be a coincidence, indeed, if the rise time of the beam voltage and the repeller voltage were identical even if the pulse modulating circuitry were matched to the pulsing elements of the klystron. This is primarily due to the fact that the high impedance of the repeller would remain constant during pulse modulation, while the beam element impedance would vary with time and therefore yield a complex impedance match even for an optimum designed pulse modulating circuit. It becomes clear that the rise time of the beam element of the klystron would be different from the rise time of the repeller element to the applied modulating pulse. The great amount of detectable frequency modulation as noted by spectrum analysis is therefore understandable, because of the changing voltage ratio of the beam element to the repeller element of the klystron.

It might be interesting to note at this point that pulsing both the repeller and beam elements of the 2K25 klystron has resulted in a relatively good spectrum. With this klystron, however, the rise time of the pulse applied to the repeller and to the beam elements was made adjustable to give an optimum spectrum. This adjustment had to be varied to suit the particular tube being pulsed and was called a "spectrum control" adjustment. This type of solution, though practical, is not desirable in military equipment where tube replacement is preferred without the necessity of adjusting circuitry.

In continuing the investigation of pulsing reflex klystrons, both the repeller and beam elements of the klystron were pulsed individually, keeping all other circuit parameters constant. That is to say, only the repeller was pulsed and the beam voltage was held constant. No effort was made to pulse tubes with control grids although, in that case, the control grid would also have been held as a constant in the test procedure.

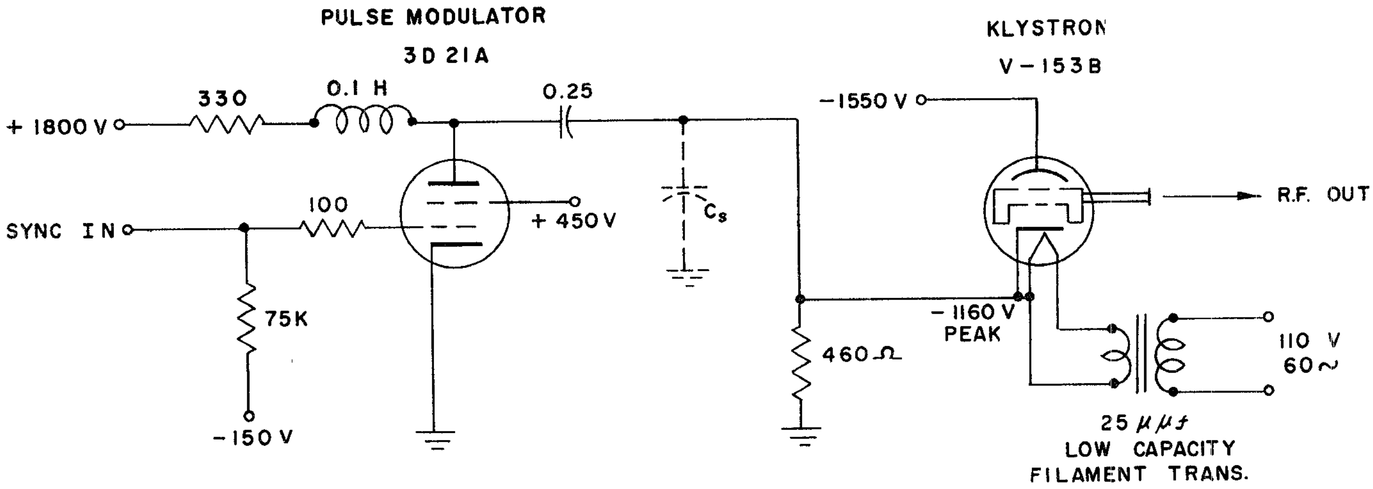

Fig. 2—Klystron beam pulsing.

Beam Voltage Pulsing

In pulsing the beam (or cathode) one has to design suitable matching circuitry to match the pulse circuitry to the characteristics of the tube being pulsed. There are, for example, a number of klystrons that operate with 300 volts beam voltage as recommended by the manufacturer, and often have the same operating repeller voltages; however, the amount of beam current drawn by the tubes could be significantly different. One can deduce, therefore, that even though several klystrons may have the same static operating voltages, the pulse impedance of the cathode or beam element of the klystrons may vary widely. The design of the pulse circuitry (Fig. 2) for optimum pulsing of the beam element of the klystron would be very similar to that of a magnetron pulser because of the requirement of operating into a circuit with a complex impedance. This has led to a compromise in impedance matching of the output pulse circuit driving the klystron beam element.

Another element of concern in pulsing the beam element of a klystron is the need for a low capacity filament transformer associated with the klystron since, in most cases, the filament is tied to the cathode of the klystron and would bypass to ground any video pulse applied to the cathode filament circuit. In general, the following conclusions were reached in pulsing the beam element of a klystron.

The detected rf video pulse seemed to have good fidelity as compared with the applied modulating video pulse, but the spectrum had no noticeable nulls generally associated with the spectrum analysis of a theoretical rectangular video pulse. It seemed to have the same kind of spectrum as associated with a theoretical applied Gaussian video pulse. This is undoubtedly due to an apparent time constant phenomenon of the beam circuit wherein the cathode circuit could not follow the rise time associated with the applied video pulse. It can be surmised that the cathode emission characteristics, electronic optics geometry, and klystron mode operation would influence this pulse characteristic of the beam element of the klystron. Some of the advantages of pulsing the beam of the klystron are: 1) The elimination of a typical high current beam power supply since the average power under pulse condition would be low; 2) The cooling blower needed with most klystrons is unnecessary because of the low average applied power.

It was also observed that as a result of the tube running relatively cool, changes of frequency due to ambient temperature variations were negligible as compared with its normally higher temperature operation during cw oscillation.

Of particular importance in beam voltage pulsing of the reflex klystrons is the fact that this technique lends itself to a very high rf peak power generation. Since the average power generated by a klystron under normal pulse operation is low, the operation of the pulse klystron at higher than rated voltages and currents is possible without exceeding the average power requirements of the tube.

The limits of the applied pulse voltage are primarily determined by the value at which voltage arc-over occurs and the point at which the maximum peak cathode current has been reached. Normally, the arc-over limit occurs first, but it is possible to provide high voltage insulation by immersing the klystron in an oil bath. This facilitates the application of higher pulse voltage necessary for peak cathode current operation. The maximum duty cycle is generally determined from the value of the maximum allowable average dc power input called out by the klystron operating characteristics. The average dc power input can be expressed by the following formula:

$$\text{Average dc power input} = (E_b)(I_b)\ (\text{Duty Cycle})$$

It is noted that the higher the desired value of peak power required, the lower is the duty cycle and conversely, the lower the desired peak power, the higher is

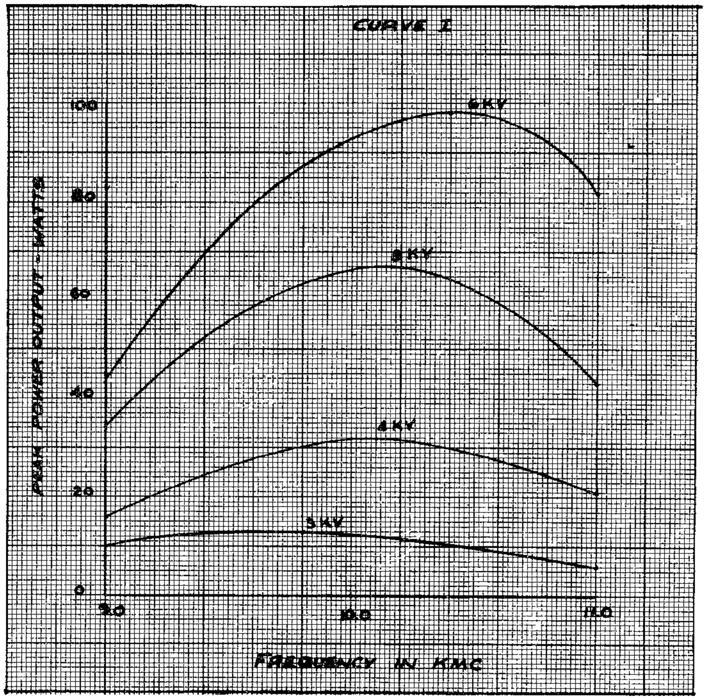

Fig. 3—2K39 pulsed power output: Curve 1—Frequency vs peak power output for various values of beam voltage. (Best mode used at each frequency. Results of three tubes averaged.)

the duty cycle. During high power pulse operation, no need for additional cooling other than that called for by cw operation is required, as long as the average input power remains the same as that recommended for cw operation. Under these operating conditions, it is felt that pulse operation will not appreciably affect the life of the klystron.

Data has been taken on the 2K39 and 2K43 reflex klystron in pulse operation,[4] and a summary of test results, will be shown graphically. In general, the pulse operation of the 2K39 reflex klystron indicated that peak power in the order of 50 to 100 watts can be achieved in the frequency range of 9 to 11 kc with applied beam voltage between 5 and 6 kilovolts. The klystron testing was carried out using a pulse repetition rate of 500 cycles per second. The rise time of the rf pulse enevelope was 0.3 microseconds and the beam voltage was about 5,000 volts. It was found that the pulse rise time did not appear to vary appreciably with load, mode, or frequency as long as the klystron was not coupled too tightly to the load. The attached curves (Figs. 3, 4, and 5) show in detail the data that was collected on 2K39 reflex klystron in pulse operation. The other klystron testing for pulse operation was the 2K43 klystron. The 2K43 Klystron is a "C" Band klystron having a minimum tuning range of 4,200 to 5,700 mc, and the typical cw operating characteristics are described as follows: Beam voltage 1,000 volts, Beam current 45 milliamperes, Power output 0.25 watts over the tuning range. The particular klystron selected for pulse operation was first tested in normal cw operation at 5,070 mc with 1,000 volts on the beam and 1,350 volts

[4] Notes on "Pulse Operation of 2K Series Klystrons," Sperry Gyroscope Corp., January 8, 1951.

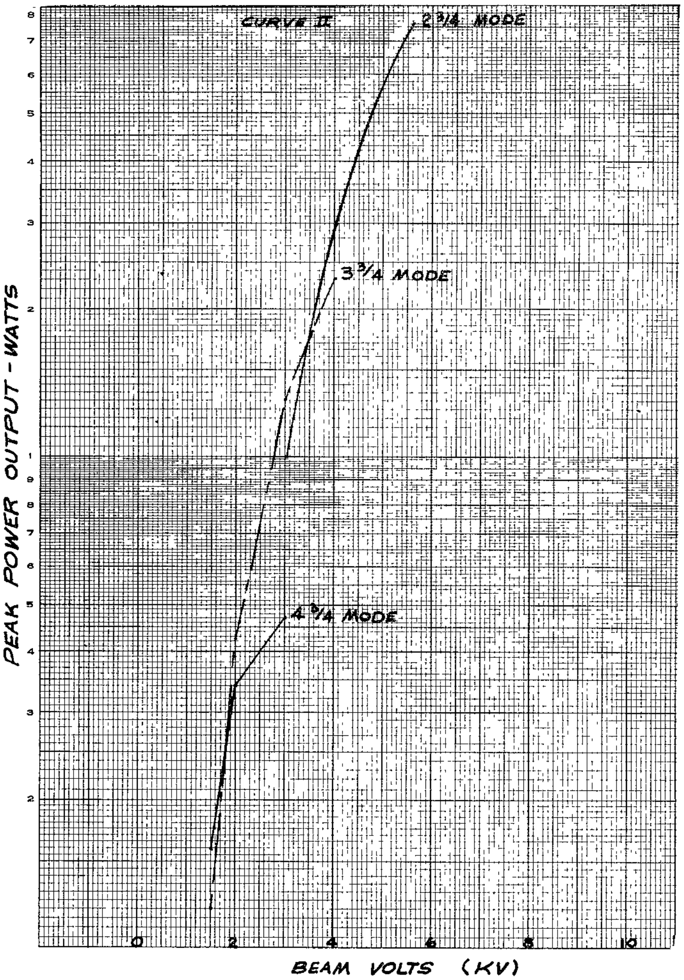

Fig. 4—2K39 klystron, frequency 9,600 mc: Curve 2—Beam voltage vs peak power output for various modes of operation.

on the repeller. The average power output under these conditions was 0.50 watt. When the beam and repeller elements were pulsed to the same cw operating voltages a peak power of 0.50 watt was measured. A PRR of 500 cps and pulse length of 2 microseconds was used for the pulse operation. By increasing the peak beam voltage, to 4,000 volts and remaining in the same repeller mode with a repeller voltage of 4,380 volts, the peak power output was increased to 18 watts. This follows closely the equation $Po = KE^{5/2}$ which governs the increase of power with beam voltage.

With the same applied beam voltage, the frequency was changed to 5,380, 5,600, and 6,000 mc. Under these conditions the power output was the same or greater. At 5,380 mc, a peak power output of 38 watts was obtained with a repeller voltage of 4,800 volts. It was noted that higher voltage repeller modes were more sensitive to external circuit loading and a variable susceptance tuner was used to optimize the load. Fig. 6 (Curve 4) shows a plot of beam voltage versus repeller voltage for four repeller modes.

Further testing at a PRR of 1, 2, and 4 kc did not result in any change in peak power output. At 4,000 volt beam operation the cathode current density was calculated to be 0.91 amps/cm-2 and the area of the cathode determined to be approximately 0.4 square centi-

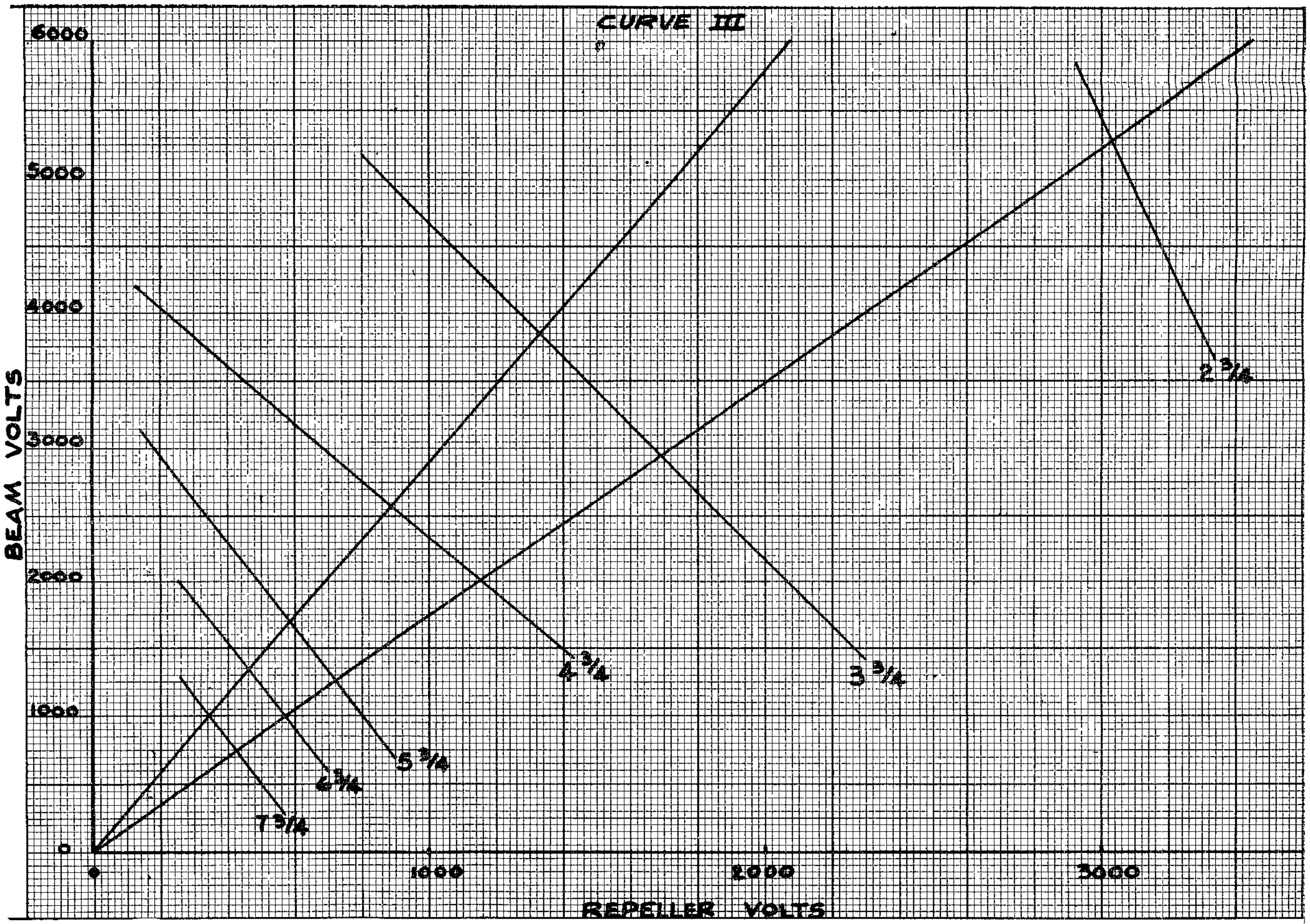

Fig. 5—2K39 klystron, pulsed frequency 9,600 mc: Curve 3—Repeller voltage vs beam voltage for various modes of oscillation.

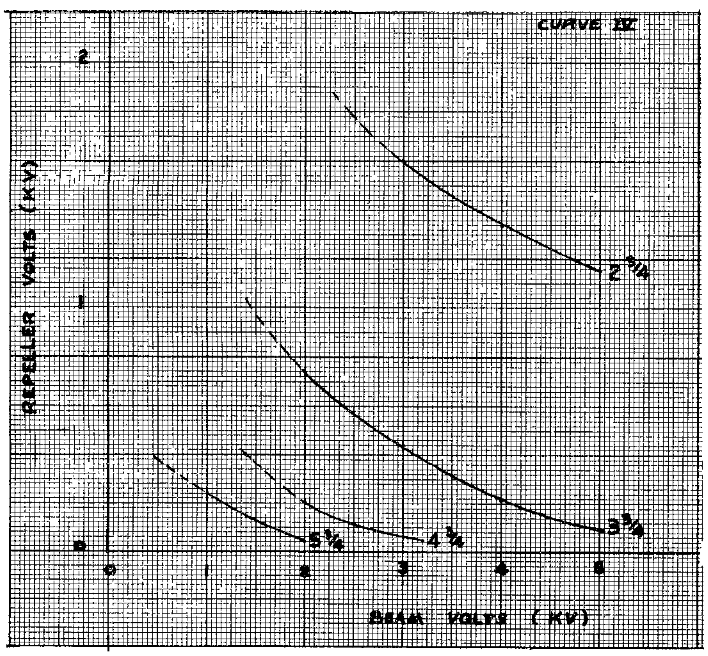

Fig. 6—2K43 klystron repeller modes, frequency 6,000 mc: Curve 4—Beam voltage vs repeller voltage for four repeller modes.

meters. To limit the repeller current to a safe operating value a parallel RC network was placed in the repeller circuit. The time constant of the RC circuit was chosen so that it was large compared to the maximum applied pulse width.

It was interesting to note that at these voltages the klystron showed no evidence of arc-over. It was also noted that as the beam voltage was increased to 5,000 volts the power output was not appreciably greater than that for 4,000 volt operation. It is suspected that klystron efficiency was dropping off at a higher beam voltage due to cathode emission limitations. Some of the disadvantages of pulsing the beam are listed below:

1) Most production klystrons currently being manufactured appear to have slightly different mode characteristics, average current characteristics, and rf matching characteristics. When optimizing the pulse circuitry for a particular klystron, there can be no assurance that any two klystrons of the same stock number will behave similarly in the same pulse circuit. This is true because the beam currents, and therefore the beam impedances, in general differ. This presents a handicap to the circuit designer who endeavors to design equipment needing a minimum of adjustments during maintenance and replacements of faulty components.
2) When pulsing beam element of a klystron, a special low capacity filament transformer is required.
3) The rf pulse is noticeably shorter than the applied video modulating pulse.
4) Modulation sensitivity of beam element is generally one-fifth that of klystron repeller modulation.

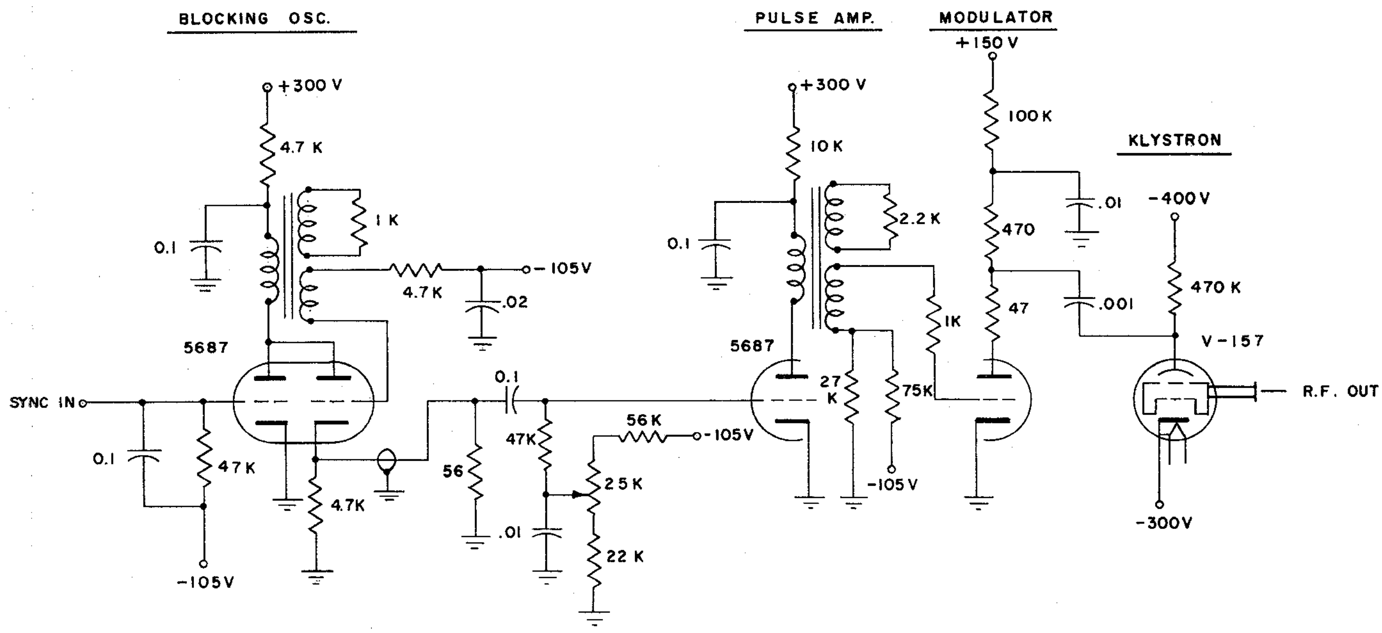

Fig. 7—Klystron repeller pulsing.

Repeller Voltage Pulsing

Pulsing the repeller of a klystron has presented the best results to pulse modulation operation. The repeller, being a high impedance circuit, does not require the special adjustment of the associated modulating pulse circuitry (Fig. 7) as for pulsing the beam element of a klystron. For this reason, interchangeability of klystrons in modulating circuitry could be rapidly accomplished without the requirements for circuit readjustment. Some of the advantages of pulsing the repeller element of the klystron are listed below:

1) It gives the best spectrum with the least amount of pulse shortening to the applied video modulating pulse.
2) It has the highest modulation sensitivity. This is particularly important when the tube is used in afc circuitry where the frequency of the klystron is controlled by changes in modulation voltage to the repeller.
3) Pulsing the repeller element does not require any special filament transformer.

Some of the disadvantages of pulsing the repeller are:

1) It requires a high current beam voltage supply.
2) High peak powers equivalent to beam pulsing cannot be realized.
3) A cooling blower is generally required.

RF Priming Technique

As a result of this background, attempts were made in the laboratory to determine optimum pulse techniques to yield minimum pulse shortening and leading edge jitter as evidenced by monitoring the detected video pulse, and qualitatively by noting the observed spectrum. Several approaches to this problem were tried, with one yielding the best results. The technique of supplying a small amount of rf power into the cavity of the klystron to be pulsed appeared to clear up all discernible pulse jitter and pulse shortening as evidenced by observation of the detected video pulse as shown by Fig. 8. The amount of energy required to prime the pulse klystron was surprisingly small. Table I shows

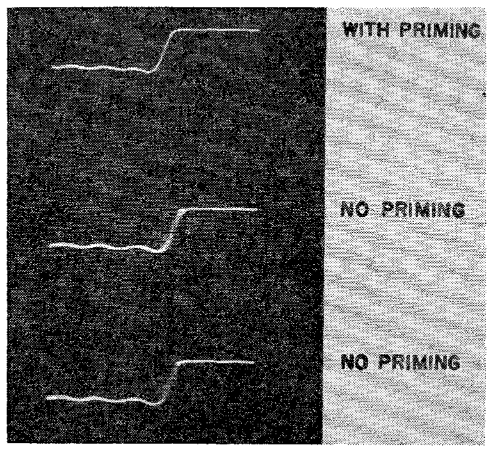

Fig. 8—Effects of priming on rf leading edge jitter.

TABLE I
Priming Frequency vs Priming Level Below Peak Pulse Power

Frequency (mc)	Primary level
9100	−10 db
9200	−25 db
9300	−34 db
9340	−40 db
9400	Jitter did not clear up
9500	Jitter did not clear up

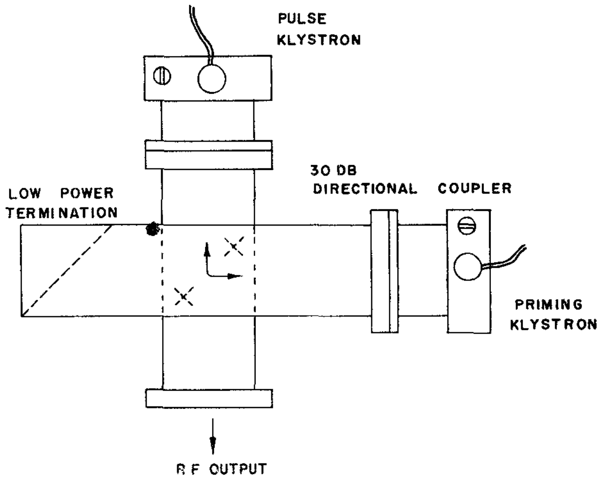

Fig. 9—Klystron priming circuit.

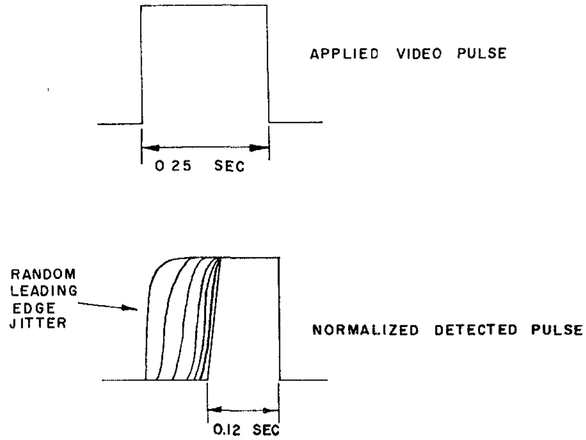

Fig. 10—X-26E klystron pulse shortening.

relative power and frequency required to prime pulse klystron. Pulsed klystron was operated at 9,360 mc and generated about +20 dbm of peak pulse power.

In general, it was observed that the frequency of the priming cw energy should be lower than the frequency of the pulse klystron and that it need be only of a very low power level. Applying priming rf above the operating frequency did not seem to clear up pulse jitter and pulse shortening. The cw priming signal was injected into the pulse klystron by means of a directional coupler (as shown in Fig. 9) but could have been injected just as well by applying some rf energy to the repeller lead of the klystron.

Fig. 8 shows the effects of cw priming of the pulse klystron. With priming there seems to be no evidence of rf leading edge jitter. Without priming the statistical leading edge jitter can be easily discerned. The synchroscope sensitivity was calibrated to be 25 millimicroseconds per centimeter and the pulse rise time was measured to be about .020 microsecond.

One other method of priming the klystron was tried, but was only a laboratory interest. In general, the technique of pulsing the repeller is accomplished by setting the static repeller voltage between operating modes of the klystron and applying a pulse to the repeller element, thus gating the tube into operation. By setting the static repeller voltage just at the edge of the lower mode of oscillation so that a very minute amount of energy was generated, and then pulsing into the middle of the next higher order mode, the jitter and pulse shortening problem was cleared up. This technique makes full use of rf energy from the lower klystron mode to prime the klystron for a higher order mode pulse operation. This technique is not recommended for equipment use because of the stringent requirements for stabilized voltages and possible spurious oscillations of the klystron operating in this marginal manner.

In one case where a 0.25-microsecond pulse was applied to the repeller of an X-26E klystron, the detected rf video pulse was only 0.12 microsecond long as shown in Fig. 10 with about 0.10 microsecond leading edge jitter. By the injection of a small amount of rf energy through a directional coupler into the cavity of the pulse klystron, the detected rf pulse assumed the 0.25-microsecond video pulse width applied to the klystron with no noticeable leading edge jitter. The minimum discernible leading edge jitter that could be accurately measured with the techniques used in this experiment was in the order of 5 millimicroseconds.

Conclusions

Rf circuit designer in selecting klystrons for pulse operation should thoroughly investigate pulse characteristics of several klystrons before making a firm choice.

External circuitry influencing the rf loading of the klystron, quality of the applied video modulating pulse, and the proper selection of klystron mode of operation are of prime importance in pulsing low power klystrons.

For generating high rf peak pulse power, beam element pulsing is recommended. Where rf pulse fidelity is required, repeller pulsing is recommended. Only in special cases where klystron tuning is accomplished during high pulse power operation, is simultaneous repeller and beam element pulsing recommended.

Acknowledgment

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