IEEE Conference Record of 1976 TWELFTH MODULATOR SYMPOSIUM

76 CH 1045—4 ED

IEEE

CONFERENCE RECORD OF

1976 TWELFTH MODULATOR SYMPOSIUM

Papers presented at the
Statler Hilton - New York City
February 4-5, 1976

Sponsored by the
IEEE Electron Devices Society
and
Advisory Group on Electron Devices
in conjunction with
Palisades Institute for Research Services, Inc.

Price: $18.00

Available from
IEEE Single Copy Sales
445 Hoes Lane
Piscataway, N. J. 08854

Printed in USA

FORWARD

The 1976 Twelfth Modulator Symposium was the latest in a series beginning with the Hydrogen Thyratron Symposium in 1950. The movement of technology can be deduced readily from examination of the proceedings and records of these conferences.

There were eight sessions which covered: Switches; High Power Switches for Intermittent Operation; High Power Modulators for Intermittent Operation; Charging Systems; Circuit Techniques; Line Type Modulators; SCR Line Type Modulators; Protective Devices and Circuits.

1976 CONFERENCE COMMITTEE

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HIGH VOLTAGE SWITCH TUBES FOR NEUTRAL BEAM INJECTORS - A NEW DESIGN APPROACH

. D.H.Preist

EIMAC Division of Varian
301 Industrial Way
San Carlos, Calif.
94070

SUMMARY

A conventional tetrode with grids cooled by radiation is an excellent choice for many applications. As a high voltage switch where current may be required for many seconds it is very unattractive because of excessive size due to the low power dissipation capability of the grids and the unfavorable voltage breakdown properties of a thin wire screen grid. The new approach would use a combination of microwave linear beam and gridded tetrode technologies to achieve a result unobtainable with either one. Well defined and separated strip beams are focussed through slot apertures in a thick screen electrode and travel some distance toward the anode without intermingling. Theoretical analysis and computer modelling indicate substantial improvement in performance: for the same electrode voltages and spacing as a conventional tetrode the current density at the anode may be nearly 2.5 times as great, or for the same current density, the spacing may be nearly 1.6 times. Also the screen electrode, being of large cross sectional area, may be water cooled, and has a much larger minimum radius of curvature than a wire grid, allowing higher voltage for a given spacing.

INTRODUCTION

A major advance in research on Controlled Thermonuclear Fusion has been the injection of neutral beams of uncharged particles which can penetrate the magnetic field containing the hot plasma and heat it much more. These neutral beams start as ion beams of low energy, subsequently accelerated to potentials of tens to hundreds of KV, after which neutralization is brought about. In the acceleration process the system arcs over frequently, making necessary a protective current limiting device. It is also necessary to start and stop the beam in a precise and repeatable manner. The most suitable device for this is a high vacuum electron tube, capable in the foreseeable future of holding off 250KV when the ion beam is cut off, passing tens to hundreds of amperes when turned on, for periods as long as 30 seconds, and equipped with a means of turning off the current in microseconds. It is also desirable that in the event of a short-circuited load, the current can be limited to a value not much higher than the normal load current. These requirements broadly suggest the classical gridded tetrode tube as a solution, and combinations of available high power tubes in series and in parallel can be and are being used in present installations. These tubes were designed and optimized for RF communications service, however, where the operating conditions are very different. It will be shown that a tube designed expressly for optimum performance and lowest cost as a switch under the conditions mentioned will tend to be quite different structurally and in its electronic behaviour from the classical tubes.

EVOLUTION OF DESIGN CONCEPT

First, the tube must hold off the applied voltage reliably. This determines the distance, or spacing, between the anode and the next electrode to it, taking into consideration the material, geometry and temperature of the electrodes. Second, the cross sectional area of the electrodes must be determined. Here, the limitation is a thermal one. The quantities of heat involved are governed by the behaviour of the electrons and in particular by space charge effects. It will be assumed throughout that the tube size should be minimized or current density maximized, since increased size inevitably means increased manufacturing cost. However, it is also necessary to minimize the power dissipated at the electrodes during conduction, since this involves cost of a different kind, in power consumption and cooling systems. In the classical tube the way these factors are related can be summarized by a few well-known equations. For simplicity and ease of understanding, we shall first assume a tetrode operated with the screen grid and anode at the same potential during conduction (the "ON" condition).

For this condition, the equation connecting these variables is as follows:

$$\frac{J_A \text{ (max.) } d^2}{V^{3/2}} = k$$

Where $J_{A\ max.}$ is the "saturated" anode current density in amps per cm^2
Where V is the anode and screen grid voltage
Where d is the screen grid to anode distance in cm
K, a constant, will be 9.33×10^{-6} for parallel plane electrodes
or 7.0×10^{-6} for cylindrical electrodes having a ratio of diameters of 2.3.

The reason for this upper limit to current density is that a potential minimum is produced between the two electrodes by the presence of the electrons. At the maximum current density this minimum falls to zero and if more current is injected through the screen grid it will not reach the anode but will arrive at the grid wires causing heating.

This equation means that if d is fixed, then an increase in anode current density (required to minimize tube size) can be obtained only by raising the voltages.

The efficiency of a tube as a switch in

the "ON" position, neglecting for the moment screen grid dissipation, is given by:

$$\eta = \frac{V_B - V_A}{V_B}$$

Where V_B is the power supply voltage

Where V_A is the tube anode to cathode voltage when maximum current flows.

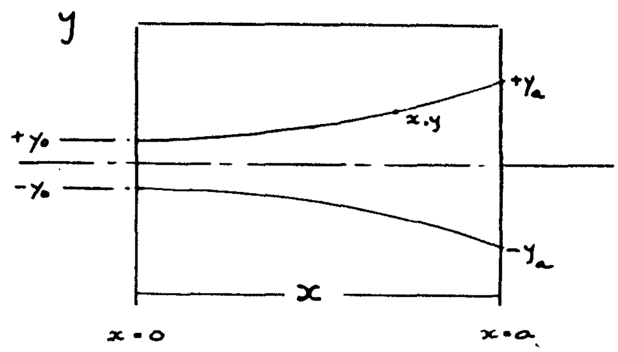
Clearly then, as a first approximation, it is desirable to use the lowest voltage for highest efficiency and the highest voltage to minimize the tube cost. A compromise is, therefore, required.

Disregarding efficiency for the moment, if the voltages are raised there will eventually be limitations on the dissipation of both screen grid and anode. In a conventional tube with grids made of wire meshes, the screen grid dissipation limit will occur first. This is because a wire grid of the size needed will be cooled essentially by radiation. This is a function of temperature. At the upper limit, set usually by primary electron emission or by continuous evolution of vapour, and for the best available materials, such a grid will radiate on the order of ten watts per cm^2 of surface area. On the other hand, the anode if water cooled can dissipate on the order of 1000 watts per cm^2. Clearly, the screen grid limitation will occur first if the current to the screen grid exceeds about one percent of the anode current, if the anode and screen grid are at the same potential. But in a typical tetrode, operated at the maximum, or saturated, anode current, the screen grid current will be on the order of ten percent of the anode current. In RF service this condition exists only at the time when the sinusoidal control grid voltage is at its peak value; the average screen grid current may be only a few percent of the average anode current. Also the average screen grid voltage may be only five to ten percent of the average anode voltage. In switching service the situation is entirely different.

Some relief may be obtained by raising the anode voltage above the screen voltage as in most tubes this will decrease the screen grid to anode current ratio, but this is obtained of course at the expense of efficiency. It would be more attractive to use a more powerful method of cooling the screen grid, such as thermal conduction or liquid cooling, or to find ways of reducing the current intercepted by the screen grid or a combination of both.

Fortunately, high power microwave tube technology has already solved a similar problem. A typical klystron tube includes an electron gun with an insulated, or "modulating", anode which may intercept less than one percent of the beam current when the anode and the rest of the tube (cavities and collector) are at the same potential. This result can be obtained in an electrostatically focussed tube or in a magnetically focussed tube using Brillouin flow where no magnetic field is present in the electron gun to help focus the beam. Also, the gun anode is typically a thick rugged member which may be liquid cooled if desired. It is reasonable to expect that strip beams obtained from gridded electron guns can be made to perform in the same way.

It is logical, then, to conceive a switch tube in which a number of strip beams are deployed in a symmetrical fashion about a central axis, each beam being generated by an electron gun preferably equipped with a control grid, the whole assemblage being mounted within or around a concentric anode. The output region of such a structure could be as shown in Figure 1. It will be of



Electron strip beam of unit depth (into paper) injected into box with potential V, velocity $\sqrt{2\eta V}$, and current density J_w.

Figure 1

interest to calculate the electron trajectories and potential distribution in this structure, assuming first that laminar and parallel electron beams are injected between the screen grid bars without interception and that these beams are free to expand without intermingling before they reach the anode.

SPACE CHARGE LIMITED ELECTRON FLOW IN FREELY EXPANDING STRIP BEAMS

Analytical

Consider a strip beam injected through a plane perpendicular to direction of motion into a region of zero electric field, such as a closed metal box. We shall assume the beam is undirectional (no components of velocity perpendicular to direction of motion) and has uniform current density. See Figure 2. This beam will expand due to space charge forces, and will satisfy Poisson's equation:

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} + \frac{d^2V}{dz^2} = -\frac{\rho}{\epsilon}$$

Where ρ is electronic charge density

Where ϵ is permittivity of free space

Where V is potential

If the beam is assumed to be infinitely wide in the Z direction, this reduces to

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} = -\frac{\rho}{\epsilon}$$

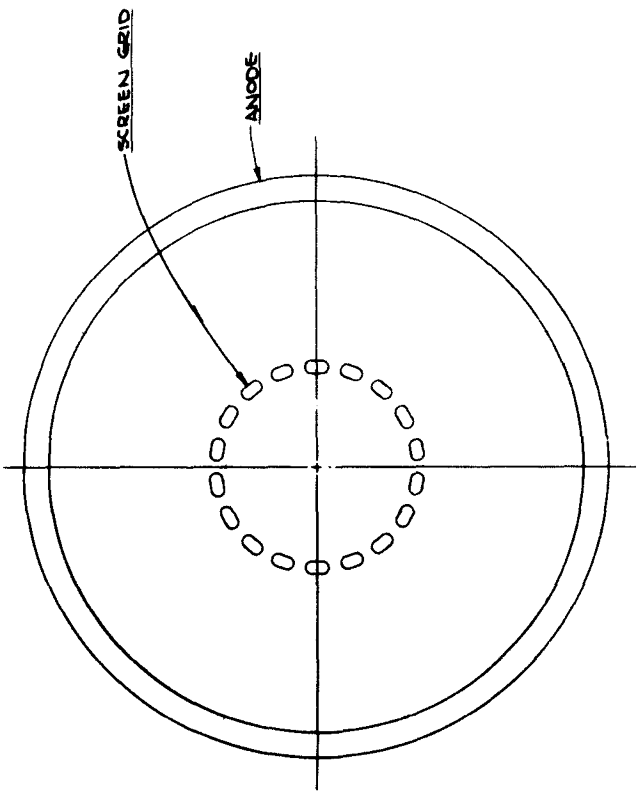


Figure 2

Since there is no potential gradient in the x direction of motion,

$$\frac{d^2V}{dy^2} = -\frac{\rho}{\epsilon}$$

following Pierce [1]

$$\frac{y}{y_o} = 1 + 2.34 \times 10^4 \frac{I}{V^{3/2}} \frac{x^2}{y_o}$$

In terms of current density at the beam waist J_w,

$$\frac{y}{y_o} = \frac{1 + 2.34 \times 10^4 J_w 2 y_o x^2}{V^{3/2} y_o}$$

$$= \frac{1 + 4.68 \times 10^4 J_w x^2}{V^{3/2}}$$

In terms of current density J_a at the plane x = a, which may be thought of as an anode,

$$J_a = J_w \frac{y_o}{y_a}$$

$$= \frac{J_w V^{3/2}}{1 + 4.68 \times 10^4 J_w x^2}$$

If $4.68 \times 10^4 J_w x^2 \gg 1$, then, very nearly,

$$\frac{J_a x^2}{V^{3/2}} = \frac{1}{4.68 \times 10^4} = 21.4 \times 10^{-6}$$

For a conventional tetrode with $V_{g_2} = V_a$ and a distance x between screen grid and anode, and parallel plane electrodes,

$$\frac{J_a x^2}{V^{3/2}} = 9.34 \times 10^{-6}$$

The ratio of the parameters $\frac{J_a x^2}{V^{3/2}}$ for the two cases will therefore approach $\frac{21.4}{9.34} = 2.29$

in the limiting case of a beam with a very large injected current density and/or a very large spread, or expansion ratio,

$$\frac{y_a}{y_o}$$

For less current density and less expansion, the ratio will be less than 2.29.

The situation analyzed, a beam expanding in a metal box, does not of course, correspond closely to the situation in a tetrode. In the tetrode, the injection plane and the anode plane are electrically conductive but the side walls of the box are missing. This situation is too complex to permit analytical solution, and, therefore, a digital computer has been programmed with this problem. The side walls can now be planes of symmetry, assumed to lie between adjacent beams which would be used in an actual multiple beam tube.

Digital Computer Calculations

Simple case of expanding beam in a metal box

To check the validity of the above calculation, the run shown as Plot 1 was made. The agreement is within about 1%.

This plot shows the potential depression which amounts to less than 15% of the injection potential.

Laminar beams injected into realistic model with planes of symmetry

Plot 2 shows an example. Electron trajectories and equipotentials are plotted. If anode current density is taken as the injected beam current divided by the beam cross-sectional area at the anode, it is found that the anode current density is 1.83 times the saturated current density assuming infinite parallel planes and uniform current density.

It is also found that the minimum potential in the freely expanding beam is two-thirds of the potential at the entrance and exit planes, instead of zero as it would be for uniform flow at saturation.

Proceeding further towards a realistic model of an actual tube, the computer was programmed with three beams so that the effects of intermingling could be studied. Plot 3 shows a typical result without intermingling, Plot 4 shows what happens when the injected current density is slightly increased and in Plot 5 there is a further increase. The beam spread is greatly increased and the potential minima inside the beams have fallen close to zero. A still further increase in injected current produces virtual cathodes and electrons are returned to the entrance plane. The limiting current is nearly twice the saturation current for uniform flow.

As another step towards a realistic model concentric cylindrical electrodes were programmed. It seemed reasonable to expect that with separated freely expanding beams the maximum anode current density would not be a strong function of the angle between beam axes, in which case an extra bonus would be obtained, since in a conventional cylindrical tube the anode current density falls off as the ratio of radii of the electrodes increases. (See constant K in equation (1) for illustration).

Plot 6 shows a typical result. Analysis shows the current density to be 0.9 times that for parallel planes. For the ratio of radii chosen the conventional tube would have a reduction of about 0.7.

Further work is planned to discover how these improvements in performance depend on the ratio of beam separation to beam entrance width, and to beam non-linearity and initial divergence.

CONCLUSIONS

The major limitation in performance of a tetrode tube of conventional construction, in very long pulse service, the screen grid heating, can be removed if liquid or conduction cooling can be used instead of radiation cooling. This requires screen grid elements of unusually large cross-sectional area. It is probable that electron guns can be developed to inject beams through the apertures in such a screen grid with acceptably small beam interception.

Mathematical analysis has indicated that tetrode tubes using separated, laminar, well collimated strip beams injected through slots in the screen grid should provide an increase in the parameter:

$$\frac{J_A \cdot x^2}{V^{3/2}}$$

Where J_A is anode current density

Where x is screen grid to anode spacing

Where V is anode and screen grid potential

compared to the value obtainable for conventional uniform electron flow

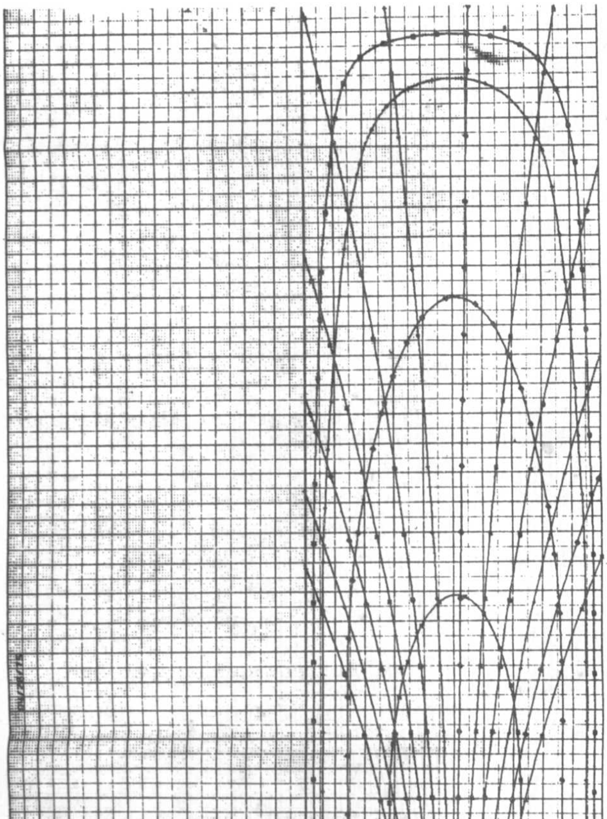
In examples calculated numerically, the increase has been found to be 1.83 for parallel plane geometry and 2.32 for cylindrical geometry with a radius ratio of 2.3 This means that for given voltage and spacing the current density can be increased by these amounts, or for a given current density the spacing can be increased by the square root of these amounts, or for a given current density and spacing the voltages and the anode dissipation can be reduced by the two-thirds power of these amounts.

More study is needed to find out how this parameter varies with beam separation to beam width ratio and beam non-laminarity and initial divergence.

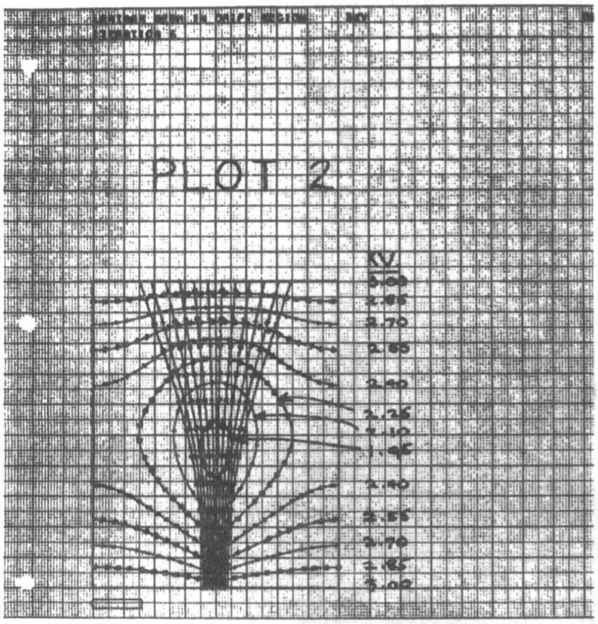
It is to be expected that the improved performance will be obtained only with beams of high electron optical quality.

It is, of course, necessary to build experimental tubes to find out if this improvement can be realized in practical devices.

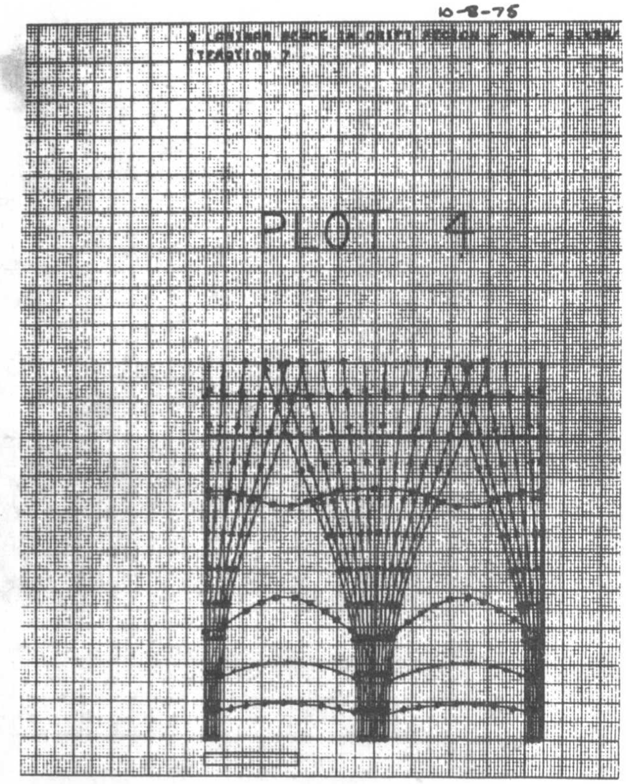
REF: 1. J. R. Pierce, "Theory & Design of Electron Beams", 2nd Edition, 1954, P.151.

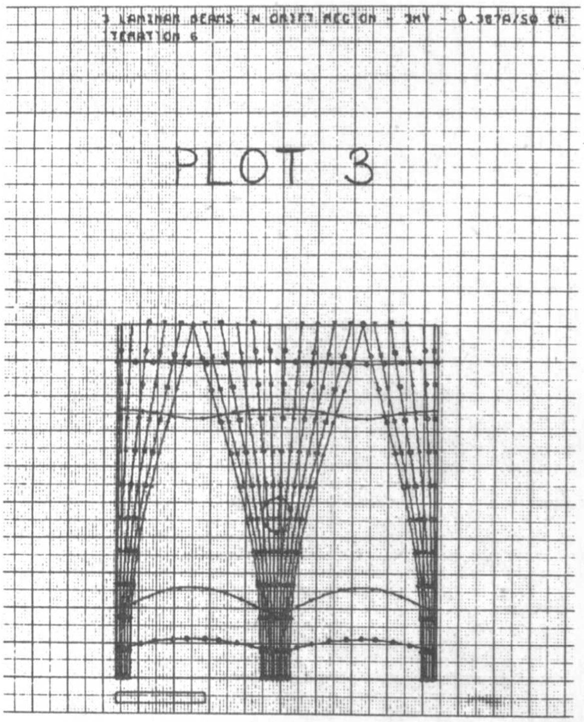


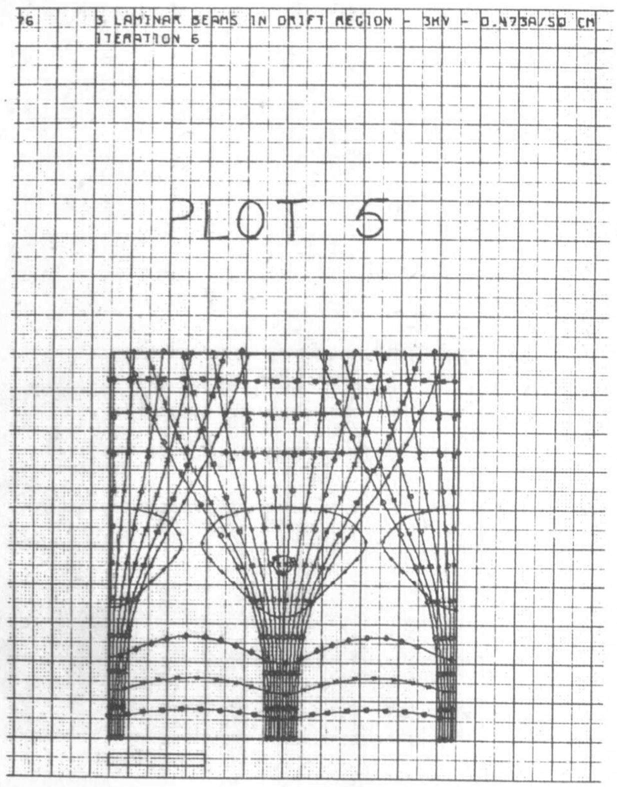
PLOT 1


PLOT 2
KV
3.00
2.85
2.70
2.55
2.40
2.25
2.10
1.95
2.40
2.55
2.70
2.85
3.00

10-8-75


ITERATION 7
PLOT 4


3 LAMINAR BEAMS IN DRIFT REGION - 3KV - 0.387A/SQ CM
ITERATION 6
PLOT 3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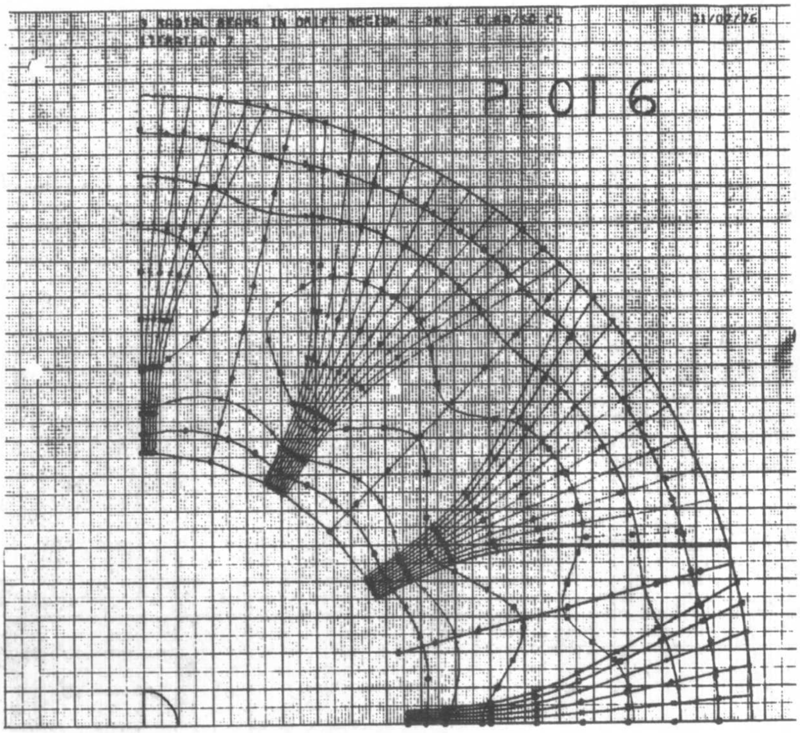
3 LAMINAR BEAMS IN DRIFT REGION - 3KV - 0.473A/SQ CM
ITERATION 6
PLOT 5


3 RADIAL BEAMS IN DRIFT REGION - 3KV
ITERATION 7
01/02/76
PLOT 6

AN EBS MODULATOR FOR HIGH POWER TRAVELING-WAVE TUBES

J. V. Stover and M. J. Westby
Hughes Aircraft Company
Fullerton, California

and

B. W. Bell and R. I. Knight
Watkins-Johnson Company
Palo Alto, California

Abstract

Switching EBS's (Electron Bombarded Semiconductors) provide high voltage, high output current capability for use in fast risetime, short time delay pulse generation. These devices have been used in the development of a versatile, high performance grid modulator for power traveling-wave tubes.

The first section of this paper describes the characteristics of the EBS which consist of a high transconductance gridded electron gun which focuses a low current (10-50 mA peak), high voltage (10 kV) electron beam onto a reverse biased semiconductor diode. The electron beam produces a current amplification of approximately 2,000 in the diode, resulting in an output pulse of several amperes. Existing switching EBS's require input pulses of 10-25 V and can provide over 7 kW peak output power.

The output risetime is controlled by the load capacitance and the peak current capability. Risetimes into a 100 pF load of 8.5 nanoseconds have been achieved at 750 V and 19 nanoseconds at 1000 V. The transit time delay through the EBS, excluding the output risetime is typically less than 2 nanoseconds.

The second section of this paper describes the practical design and implementation of the EBS switch into a grid modulated TWT pulse amplifier. The EBS modulator provides up to 900 V peak grid voltage swings over pulse width ranges of 0.1 to 1.8 microseconds. The performance, size and weight of the EBS modulator is presented and compared with an all transistor modulator.

The projected effect of improved EBS performance on the overall modulator performance will be described.

Introduction

The switching EBS offers advantages over the use of other switching devices such as transistors or hard tubes, specifically in the areas of pulse risetime, internal delay, high PRF operation, and reliability. The EBS can switch voltages up to 1000 V with risetimes between 3 and 30 nanoseconds depending on the load impedance and capacitance, while the delay through the tube is typically only 2 nanoseconds. Switching EBS's have demonstrated operation at duty cycles as high as 60% and PRF's as high as 2.5 MHz. Switching EBS's can also be designed with arc protection circuitry which results in no damage to the switching EBS due to arcs by the TWT being modulated. In addition, EBS devices have demonstrated MTTF's in excess of 100,000 hours. Switching EBS's which have previously been built at Watkins-Johnson have included the WJ-3652, a high current device capable of switching 100 V with 100 A of peak current in 3 nanoseconds; the WJ-3653 and WJ-3684, both 400 V, 4 A devices; the WJ-3683, a dual output 400 V pulse amplifier; and the WJ-3680, a 750 V, 7 A device.

Theory of Operation

The switching EBS consists of a high transconductance gridded electron gun and a reverse biased silicon diode, as shown in Fig. 1. The grid is normally biased in cut-off and the only current flowing in the external circuit is a small diode leakage current, typically less than 1 mA. When a positive pulse is applied to the grid, the diode is illuminated by a beam of high voltage electrons. These 10-15 kV electrons penetrate the thin surface contact of the semiconductor diode and create a large number of electron-hole pairs by impact ionization. Formation of a single electron-hole pair requires 3.6 eV; the current gain in the semiconductor diode is given by

$$a = \frac{V_k - V_1}{3.6\ \text{eV}}$$

V_k - Cathode voltage

V_1 - Junction penetration loss (Typically 3-5 kV)

Typical values for the diode current gain range from 1500 to 3000. As a result, relatively small electron beam currents can control large currents in the output circuit.

Static operating characteristics for a typical EBS are shown in Fig. 2. This curve shows the diode current as a function of diode bias for a number of control grid voltages. The characteristic curve may be divided into three regions. Above voltage V_a the diode is in avalanche breakdown. To avoid damage the EBS must never be allowed to operate in this region. Region II is the active region in which the EBS acts as a high impedance current source. When operated in this region, the EBS behaves as a broadband video amplifier. Carrier transport within the diode is entirely by drift at high velocity rather than by diffusion, as in many semiconductor devices. As a result, there is no carrier storage time other than the extremely short transit time. For this reason an EBS operating in the active region may be turned "on" or "off" with equal rapidity.

Region III is the saturation region in which substantial storage time may arise due to the injection of excess beam current into the diode. This excess current will stretch the pulse width and increase the fall time. However, operation in this mode presents two primary advantages; first, the load impedance is typically greater than 1000 ohms, as opposed to the 100 ohm or lower load impedance when operating in the active region. This higher load impedance greatly reduces the power dissipated in the diode, allowing operation at very high duty cycles. The second advantage is that by operating in saturation, the sensitivity of the output voltage with respect to variations in the grid drive or cathode voltages is greatly reduced. For these reasons, the switching EBS's are operated in the saturation region in the EBS modulator. However, special steps are taken to eliminate the stored charge and to achieve a fast fall time. These techniques, which will be discussed in greater detail in the second section of the paper, involve the use of clamp circuitry to prevent the accumulation of stored charge and the use of a second EBS device to act as a "tail-biter" to achieve the fast fall time.

Tube Design

The original design of the 1000 V switching EBS used two parallel diode strings of 3 diodes each, with the diodes of the type originally used in the WJ-3653 400 V switching EBS. However, during testing of the prototype models, it was found that the diodes would stabilize with breakdown voltages between 300 and 350 V. Hence, the tube was redesigned to utilize four diodes in series; because of the length of the array and the large number of diodes, only one string of diodes was used. A photograph of a completed target is shown in Fig. 3. Note that tabs are provided for electrical connection to each point in the diode array. With this design it was possible to consistently fabricate arrays with stable breakdown voltages greater than 1200 V. In addition, the use of the fourth diode provided an extra reliability factor in that if one of the diodes were to fail, the unit would still be capable of operation at 900 V peak output, the maximum voltage swing required to drive the TWT's.

The mechanical design of the 1000 V switching EBS was based on the design of the WJ-3653, with the target holder modified to accept the larger target. A photograph of the completed tube is shown in Fig. 4. The five bias pins allow the use of an external voltage division network to equalize the voltages across the four diodes.

Device Performance

The device performance and electrical characteristics are summarized in Table I. The performance values are given for operation into a 5 k-ohm load shunted by 100 pF capacitance. The risetime of the device will be limited by the 3.5 A of peak current available to charge the load capacitance; Fig. 5 graphs the output risetime versus load capacitance measured for WJ-3680-3 S/N 16. When operating into a primarily capacitive load, the major amount of power dissipation in the diode is caused by the charging and discharging of the load capacitance at high PRF's. The power dissipation under these conditions is given by the following formula:

$$P = 1/2\ (C_{diode} + C_L) \times V^2 \times PRF$$

C_d - Diode capacitance

C_1 - Load capacitance

V - Peak voltage swing

Thus with a diode plus load capacitance of 150 pF, an output pulse voltage of 1000 V, and a PRF of 200 kHz, the diode power dissipation would be 15 W.

Testing of the original units revealed that the cathode current would shift downward with increasing PRF even when the grid voltage was held constant. This change in cathode current, which is discussed in more detail in the second part of the paper, made it difficult to adjust the EBS modulator to operate over a wide range of PRF's. The cause of this decrease was traced to partial poisoning of the cathode, most likely caused by the diode target. To correct the problem, a new activation schedule in conjunction with a higher temperature bake-out was instituted. These techniques resulted in a marked improvement in the performance of the remaining devices delivered.

Due to the processing complexity involved in achieving satisfactory performance from the oxide cathodes used in the switching EBS's, testing has been done on the use of impregnated cathodes. This has resulted in the design and testing of switching EBS's which show no variation in cathode current, while the better oxide cathode would show 5% change from 100 Hz to 20 kHz. Dispenser cathodes are now being used in the WJ-3684 switching EBS, and will be used in the 1000 V switching EBS's provided for the EBS modulator. The use of the dispenser cathode has had an additional advantage; because of the reduced processing required and because of the reusability of the cathodes, it has been possible to significantly reduce the cost of the devices.

Testing of the switching EBS's in the EBS modulator has led to a second modification in the design of the switching EBS. During operation of the devices in the EBS modulator, it was found that after the units had been allowed to sit for several weeks without operating, an arc would occur between grid and target during initial application of high voltage. The arcing was apparently occurring along the ceramic insulating surface. Any arcing across the ceramic surface would most likely be caused by contaminants deposited on the ceramic during outgassing of the tube. To solve this problem, the outgassing path was modified so that the ceramic was shielded from most contaminants, particularly those resulting from cathode activation.

Further Device Development

The 1000 V switching EBS's supplied for the EBS modulator contain the four diode series configuration. As was mentioned earlier, this design was selected based upon the achievable stable breakdown voltages of the diodes. Since that time, Watkins-Johnson Company has developed their own capability to design and fabricate the EBS diodes. The facility, in operation since April of 1975, has resulted in the fabrication of diodes of the type used in the EBS modulator with initial breakdown voltages of 600 to 650 V. The stabilized breakdown voltage, after exposure to the electron beam, is typically 550 to 600 V.

The diode fabrication capability has led to the feasibility of fabricating switching EBS's with the six diode target originally proposed for the EBS modulator. The use of this device would result in a 50% improvement in the risetime and fall time capability of the EBS modulator, as well as the ability to operate with narrower pulse widths.

A second type of device currently being fabricated by Watkins-Johnson Company utilizes a single high-voltage diode target. The initial breakdown voltage for the high-voltage diodes is typically 1100 to 1200 V. Upon stabilization after exposure to the electron beam, these diodes have breakdown voltages of typically 800 to 900 V. The single diode target has several advantages: first, the diode can be fabricated with a relatively large area, resulting in high output currents. The diodes used in the four diode series target have an active area of 2 mm^2, whereas the high-voltage diodes have an area of 19 mm^2. A photograph comparing the two diode targets is shown in Fig. 6. The larger area results in an output current capability of greater than 12 A. The use of a switching EBS of this type in the EBS modulator would reduce the rise and fall times to about 10 nanoseconds. A second advantage of the high-voltage diode is the power dissipation capability. Due to the large area, the power dissipation rating of the tube could be doubled while maintaining the same power dissipation capability per unit area. A third advantage of the diode is that due to the fabrication of the diode in a circular geometry, the part of the beam actually striking the diode is 60%, whereas for the four diode series configuration the ratio of current striking the diode to total beam current is less than 10%. Not only would this simplify power supply requirements, it would also mean that the EBS would require less grid drive voltage. As mentioned in Part II of the paper, the present EBS modulator uses a spiked grid pulse with a maximum amplitude of +40 V. With the new diode, this could be reduced to +5 V. A fourth advantage is, since the single diode has a smaller effective radius than the present target, it is possible to design it into a tube with smaller overall dimensions. A photograph of the two units is shown in Fig. 7. Both the size and weight of the single diode unit, the WJ-3681 have been reduced 50%.

As mentioned previously, the present limitation on output voltage of the WJ-3681 is approximately 750 V. Work is progressing on fabrication of the higher voltage diodes. Three approaches are currently being pursued; the first is the use of less highly doped material. This has recently resulted in the fabrication of diodes with 1400 V breakdown voltages. The second approach is the continued use of the planar diode geometry but with different guard ring depths and multiple guard rings. The third and most promising approach is the use of mesa diodes. This technique has led to the development of diodes with greater than 1500 V breakdown, although these diodes would not have been suitable for use in vacuum due to the lack of any passivation. However, techniques are currently being developed to fabricate passivated EBS mesa geometry diodes which are expected to result in diodes with greater than 1500 V breakdown voltages. With an initial breakdown voltage of 1500 V, the stabilized breakdown voltages of these diodes would be on the order of 1300 V, fully suitable for use in the EBS modulator. Table II gives a comparison of the performance specifications of the WJ-3680-3 switching EBS presently used in the EBS modulator and the WJ-3681 utilizing the single diode target.

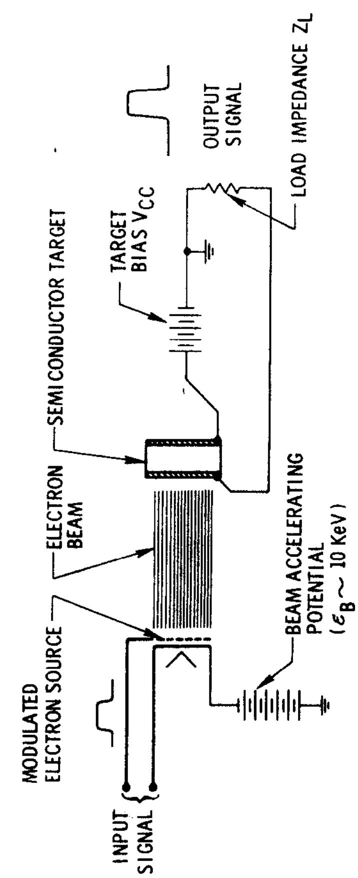


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Fig. I-1 Schematic showing internal components of switching EBS.

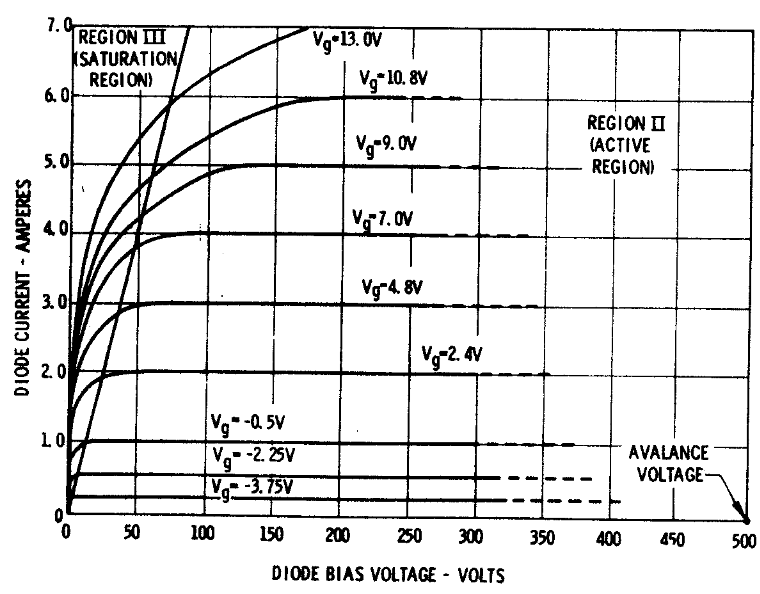

Fig. I-2 Static operating characteristic showing output current versus diode voltage for different grid pulse voltages.

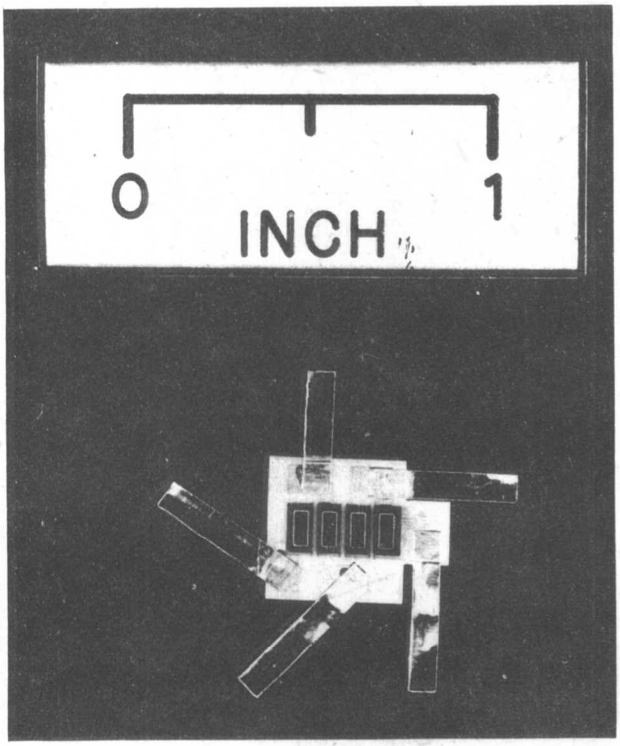

Fig. I-3 Photograph showing completed four diode series target.

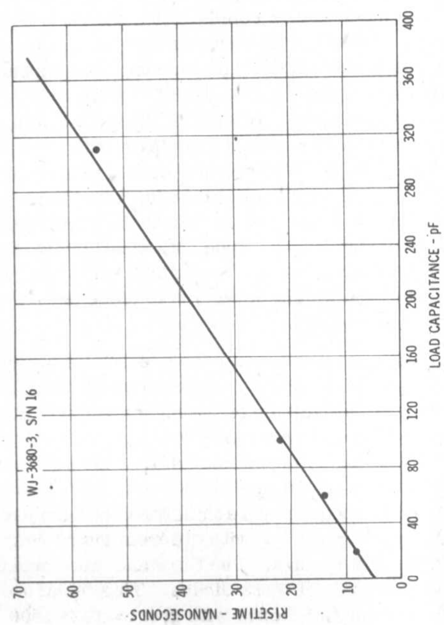

Fig. I-5 Measured risetime versus load capacitance for WJ-3680-3 S/N 16.

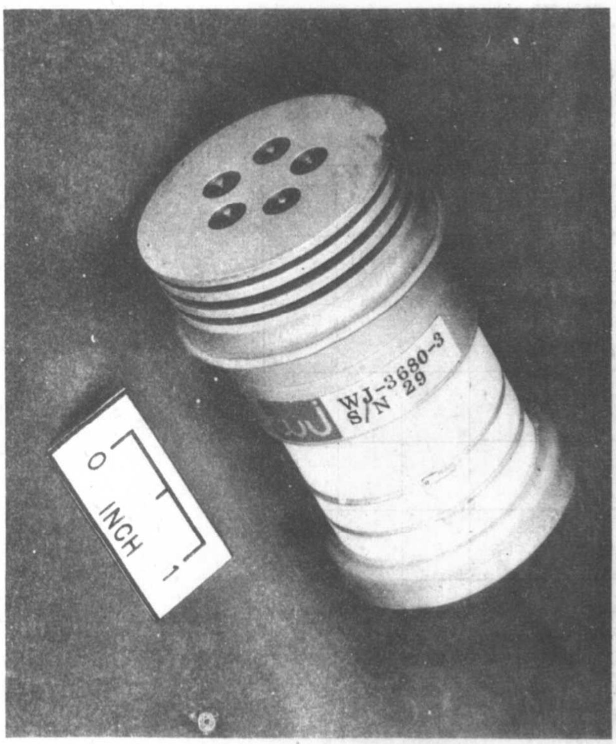

Fig. I-4 Photograph showing 1000 V switching EBS.

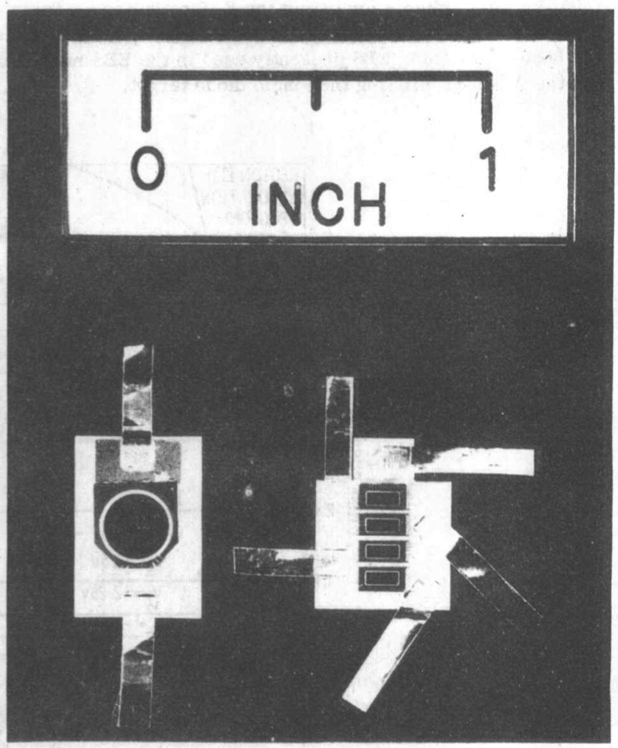

Fig. I-6 Photograph comparing the four diode series target with the high voltage single diode target.

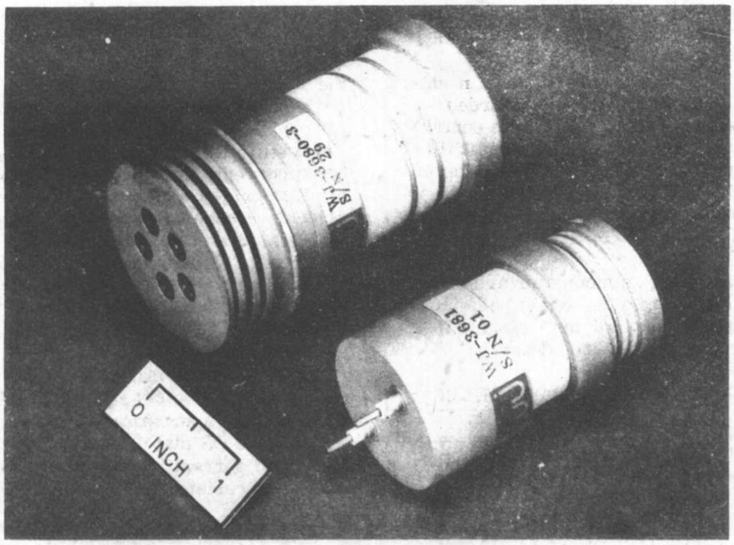

Fig. I-7 Photograph comparing the size of the WJ-3680-3 presently used in the EBS Modulator with the reduced size WJ-3681.

TABLE I

WJ-3680-3
ELECTRON BOMBARDED SEMICONDUCTOR (EBS)
1000 VOLT SWITCH

PERFORMANCE CHARACTERISTICS	VALUES
2.5K ohm, 100pF LOAD	
PEAK OUTPUT VOLTAGE	1000V
PEAK OUTPUT CURRENT	3.5A
OUTPUT RISETIME	25 ns
DELAY (10% input - 10% output)	2 ns
DIODE POWER DISSIPATION	15W, max.
PULSE REPETITION FREQUENCY	200 KHz, max.
PULSE DURATION	50usec, max.
DUTY CYCLE	10%, max.

TABLE II

COMPARISON OF SINGLE DIODE VS. 4 DIODE PERFORMANCE

PERFORMANCE CHARACTERISTICS	VALUES	
2.5K ohm, 100 pF LOAD	WJ-3680-3	WJ-3681
PEAK OUTPUT VOLTAGE	1000 V	750 V
PEAK OUTPUT CURRENT	3.5A	12A
OUTPUT RISETIME	25 ns	10 ns
DELAY (10% input - 10% output)	2 ns	2 ns
DIODE POWER DISSIPATION	15W	25W
PULSE REPETITION FREQUENCY	200 KHz	350 KHz
PULSE DURATION	50usec	50usec
DUTY CYCLE	10%	10%