

## TRIODES AND KLYSTRONS AT ULTRA-HIGH FREQUENCY

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Triodes and klystrons are compared, especially with respect to the internal voltage gradients and emission current densities necessary in designs to serve as r-f power sources for the high intensity, high energy proton linear accelerators now in planning at Los Alamos and at Brookhaven.

Either triodes or klystrons might be used in these applications, but in order to supply the power needed, a triode will have to be operated near the limits of what is possible, particularly with respect to the capabilities of the emitter. The klystron, in contrast, will not require that any electrical or materials limit be approached at all closely. Many times the power needed, both peak and average, have been generated at frequencies higher than 800 Mc by klystrons. The klystron thus possesses adequate power reserves and would be a more reliable source of power.

### Introduction

The choice of the best source of radio-frequency power is an important decision in the design of any particle accelerator. A properly operating power source is vital to the usefulness of any accelerator, but some accelerators are more tolerant of flaws and partial failures than others.

The range of options is, more frequently than not, dictated by the operating frequency. At the low frequencies used in the various forms of the cyclotron and in proton synchrotrons, the choice is among the various triode or tetrode power tubes that are widely employed in other services, and they are usually run well below their nominal ratings.

The combination of ample power reserves in the tubes and only a few tubes in the power source have made the r-f power sources of circular machines satisfactorily reliable.

The various proton linear accelerators, used as independent tools or as injectors for the big circular machines, are not extremely demanding either. Although the frequency in many is around 200 Mc, the peak power (a few megawatts) is not large for this frequency and not many tubes are used in the power source.

The power sources used with electron linear accelerators are almost universally klystrons. Some accelerators are operated at about 1200 Mc but the most usual operating frequency is 2850 Mc, and the power per tube is as high as 25 Megawatts. A typical

power tube for an electron linear accelerator then operates at ten times the power and fourteen times the frequency of the power tubes now used to power linear accelerators for protons.

The average tube life of the klystrons used to power electron linear accelerators has not been as good as that of the triodes and tetrodes used in proton linear accelerators, and it would be very surprising if it were. The voltage gradients and power densities everywhere in the tube and the output transmission line are far above those in the tubes used in the proton linear accelerators which have been built so far.

In most respects, the choice of the best source of radio-frequency power for a high-energy, high intensity linear accelerator for protons is more critical than for any particle accelerator yet built. That large numbers of tubes must operate simultaneously puts a premium on reliability far beyond that of the lower-frequency, lower energy machines or of the electron linear accelerators.

The emphasis here will be on a comparison of Klystrons with Ultra-High-Frequency Triodes as possible power sources for this class of accelerator. The discussion cannot be wholly divorced from specific tube types and manufacturers.

A basic premise is assumed. It is, that any secondary electrical characteristic can be accommodated, if the particular characteristic is uniform from tube-to-tube and stable with time. The system consequences of the various external electrical differences between UHF triodes and klystrons have been described by Morris and Martin-Vegue<sup>5</sup> and will not be discussed in detail here. The primary electrical attributes are gain, efficiency, power output capability including reserves, and resistance to damage. The secondary characteristics are phase shift with supply voltages, and coupling between output phase and amplitude.

With respect to gain, efficiency and the capability of much higher power than is required, the advantage at 805 Mc is all with the klystron. Gain is important in that it allows reduction of the number of tubes in the system. The efficiency difference is not great, but the advantage again is with the klystron. It is in the basic capability of the structure that the klystron's advantage is overwhelming. It would be feasible to build a 1.25 Megawatt C-W klystron at 805 Mc, or a 25 Megawatt peak, 1 Megawatt average power tube, if that were needed. A triode, to develop 1.25 Megawatts peak and

75 Kilowatts average power, will strain nature's limits on emission density, voltage gradients and power density most severely.

Even the secondary characteristics are not wholly to the disadvantage of the klystron. The output phase/amplitude coupling is nearly the same for a triode or klystron when the output amplitude changes as a result of load changes. The output phase is more strongly coupled to the amplitude in a klystron than in a triode when the r-f drive power is changed. The output phase of a klystron is more dependent on supply voltages, but less than 1/20 of the current needs to be regulated.<sup>5</sup>

The emphasis here is on the internal differences and similarities of the two tube types, on the demands each make in terms of emission current density from the cathode, the voltage gradients in the gun and the interaction circuits, and the power dissipation requirements on the various parts of the tube. It is almost impossible to discuss such considerations in a general sense, so we compare what happens in two different tube types designed for the same service.

High frequency power amplifiers fail in little things, a focus electrode or grid may start to emit after a long time in service because it has become sufficiently dirty, or it may suffer internal dielectric breakdown because a grid wire or a filament has been heated and cooled too many times and broken because of it, or the coolant passages have become clogged. Many different things happen. It seems certain though that a tube design which minimizes the various stresses which can occur will have a better chance of lasting a long time than a tube which approaches any limit closely.

Reliability in operation is regarded as the single most important attribute of the power source.

#### Limitations, Ratings and Failures

Anyone who has designed or used vacuum tubes is aware that the life and reliability of a vacuum tube is frequently improved by lowering the applied voltages and the standards of performance demanded. He is also aware that any vacuum tube can be destroyed if the potentials applied to it are high enough.

Enhancement of tube life by the reduction of the demands on it must be done intelligently. In most instances it would do little good to reduce the power output of a klystron amplifier by reducing the signal power driving it, and it would probably not be of benefit to reduce the output power of a UHF triode by lowering the plate voltage, unless the filament temperature is also reduced. The klystron amplifier would be benefitted only if voltage breakdown in the output transmission line and output seal rupture were a common cause of failure. The UHF triode would gain mostly from the lowered

filament temperature, since the most frequent causes of failure in these types are filament-related.<sup>4</sup>

Limitations are imposed by nature on the performance of vacuum tubes, ratings are the tube manufacturers estimates of how closely we can safely approach the limitations imposed by nature. Ratings that reasonably represent the performance and limitations of vacuum tubes can be derived from tests and experience when large numbers of the tubes have been built over a span of time large enough that significant numbers of the tubes have been subject to stable field experience. This is most frequently not the case for high-power UHF and microwave amplifiers. The ratings here are usually a reflection of what the tube must do to meet the specifications of a contract or a purchase order.

#### Tube Designs

Although it maybe undesirable in some respects, it seems necessary to compare a particular design of a triode with a klystron designed for the same service.

The triode that is examined is a one-half scale model of the RCA A-15038 Coaxitron, which is rated at 5 Mw peak, 75 kW average at approximately 400 Mc. On a constant power-per-unit-area basis (or emission density), this scaling would give 1.25 Mw peak and 19 kW average at 800 Mc.

The A-15038 is a Coaxitron version of the A-2346. The details of this development are available in references 1, 2 and 3. The A-2346F is familiar to some as the 7835 and the A-2346N is offered as the 2054.

The Coaxitron concept of building the resonant circuits as part of a triode amplifier is an outgrowth of the A-2346 development and represents a response to some of the difficulties experienced in that program. External cavities were used with the A-2346 so that the whole amplifier would be tunable. The Coaxitron uses a fixed-tuned half-wavelength resonator, which improves the bandwidth and circuit efficiency over that of the three-halves wavelength resonators of the A-2346, but at the expense of tunability.

The scaling process from 400 to 800 Mc at constant emission density doubles the voltage gradients within the tube, or said another way, the gradients in the 800 Mc tube are equivalent to those of a 7835 run at 60 kv plate voltage.

A one-half scale model of the A-15038 is assumed to be at least a reasonable approximation to the A-15191, an 805 Mc Coaxitron rated at 1.25 Mw peak power and 12.5 kW average power. The scaling process results in a double-layer grid of 0.0016" wire spaced on 0.005" centers and wound at 144 turns/inch.

Whether the grid wire has been reduced to 0.0016" from 0.003" does not matter much, a few minutes reflection will reveal that the grid wire size does not affect the voltage gradient at the grid, so long as the plate to grid distance is large compared to the grid wire spacing and the ratio of wire diameter to spacing between wires is constant.

The klystron is hypothetical, a blend of scaling from successful past practice and the author's opinions as to the most desirable design features for this application. It would be a three or four cavity, solenoid focus, fixed tuned amplifier, vapor cooled and insulated with pressurized air.

The electrical parameters for both the triode and the klystron are given in Table I.

#### Cathodes, Voltage Gradients and Power Density

It would be impossible, in the space available here, to discuss the behavior of either triodes or klystrons in large-signal conditions and at high frequencies in enough detail to be meaningful. Several such discussions appear in standard textbooks and in the technical literature. Dow<sup>6</sup> discussed the principles important in the design and use of triodes for Class C service at frequencies high enough that electron transit time is important. He pointed out that, by increasing the voltage and current density simultaneously, the power and efficiency can be raised without sacrificing bandwidth. It is apparent though that this process cannot be continued indefinitely, properties of materials and electric field limitations will intervene at some frequency and power level.

The designer of a high-power UHF triode is faced with several unsatisfactory choices.<sup>6,7</sup>

If the plate-to-grid (output gap) spacing is made small enough that transit time is negligible, the circuit efficiency is poor. Bennett and Kaznowski<sup>7</sup> found they could improve the output efficiency by increasing the output gap and trading electronic efficiency for improved circuit efficiency.

$$(\eta = \eta_e \cdot \eta_c)$$

The output-gap transit angles in the A-15038 and its 800 Mc image are not as large as is customary in klystrons. But they are not negligible either. For 10 kv on the plate, the transit angle (d-c) is 0.66 radians, the transit angle at 40 kv is 0.33 radians. The electron transit time in the grid region for a steady 150 V grid voltage is 0.57 radians. The output gap transit angle in a klystron is, for most power tubes, about one radian.

The principal practical effects of transit time in a triode are that the maximum plate current no longer occurs at the instant the plate voltage is a minimum,

and the minimum plate voltage is a larger fraction of the d-c plate voltage.

That the transit time is appreciable makes both the input and output regions act like "reactance" tubes. The higher minimum plate voltage is the principal reason the efficiency of the UHF triode is less than that of a low frequency triode.

The emitter of triode must supply the peak current of the r-f cycle. The emitter of a klystron needs to supply just the average beam current. For the scaled A-15038, the average plate current during the r-f pulse is 80 amperes. In a Class B amplifier the current at the peak of the r-f cycle is  $\pi$  times the average current, or in this case, about 250 amperes. About 1/3 more is intercepted by the grid<sup>1</sup> so the total current demanded of the plate-facing side of the emitter is about 330 amperes. (Another 170 amperes, mainly from the back side, goes to the dead parts of the grid structure.)

The emitting area of the scaled A-15038 is about 75 square centimeters so the emitter must be capable of supplying 4.4 amperes per square centimeter. The predicted life for a thoriated-tungsten emitter carburized to a skin depth of 0.005" and run at 2050°K is 14,000 hours.<sup>1</sup>

The gun chosen for the klystron is a half-scale model of that used in a successful klystron. It was chosen because the emission density needed is satisfactorily low, no iron is required in the vacuum, and the voltage gradients are low. The cathode is of barium-impregnated tungsten and 2.4" diameter.

For 40 amperes current, the current density will be 1.4 amperes per square centimeter and the operating temperature will be 1300°K. The indirect heater will run at about 1700°K.

Brodie<sup>8,9</sup> estimates the life of this cathode (1mm thick, 25% porous, 1/2 CaO·3 BaO·Al<sub>2</sub>O<sub>3</sub> impregnated) to be  $5 \times 10^5$  hours (57 years).

The voltage gradients in the gun are so low as to be of no concern in either the triode or the klystron. The maximum gradient in the triode (at the grid wire) is about 30 kv/cm when the grid-cathode voltage is 150 volts. The maximum gradient in the klystron gun, at the focus ring facing the anode, is 53 kv/cm.

The gradients in the output region of the triode are much higher than those in a klystron, but they are still within the range of successful experience. At 40 kv plate voltage and 0.142" spacing, the averaged gradient is 110 kv/cm. The maximum gradient, which occurs at the surface of the grid wire, is more than twice the averaged gradient and is 250 kv/cm for the d-c holdoff alone. If the peak r-f voltage is added (30 kv) the maximum field becomes 450 kv/cm or 45

megavolts per meter.

The situation is much easier with a klystron gap. No d-c voltage is present and the gap is much larger. At 75 kv beam voltage, the peak r-f voltage might be as high as 90 kv. The output gap will be one inch long so the averaged gradient will be 35 kv/cm and the maximum gradient, 70 kv/cm.

The output resonant circuit of a triode must dissipate the entire waste plate power in addition to its circuit functions. These functions are neatly separated in a klystron. If we assume 33% efficiency for the scaled A-15038 and 75 kW output power average, the plate must dissipate 150 kW. The plate is 3.656" diameter and 2" long, a total area of 150 square centimeters. The plate must therefore dissipate about 1 kW per square centimeter in normal conditions. Cracking of the anode face was experienced in the A-2346 development<sup>1</sup> at 2 milliseconds pulse length when the anode faces were plane surfaces. The problem was alleviated by making the anode surface an array of pyramids to allow the heated surface to expand and contract without restriction during the pulses. This may be an effective technique.

The waste power of a klystron can be spread almost arbitrarily since the collector is not part of the r-f circuits. The power density at the collector is usually about 300 watts per square centimeter.

#### Operation into a High-Q Load

The mechanism of energy exchange from d-c to r-f is the same for a triode as for a klystron. Both types convert d-c power to r-f power by forming a tight bunch of electrons and then slowing it down in an opposing r-f field. When the electron bunch arrives at the output gap of either device, there is little to distinguish them.

Both devices, a high  $\mu$  triode in a grid-separation circuit and a klystron, can be accurately represented as constant current generators, at least in the region where the load conductance is large compared to the optimum load. (Fig. 1) If the output "detuned short" of the generator is made to coincide with the "detuned short" of the accelerator cavity the build-up in charging the cavity is particularly simple. The envelope of the transient is simply that of a parallel R-C combination driven by a constant current source.

If the output window is placed such that it is at the detuned short, the electric field at the window will never (in the charging transient) exceed that corresponding to maximum power into a matched load, and neither device should need an isolator for protection.

The output power vs load conductance for a klystron amplifier is given in Figure 1. This is normalized

measured data, not computations. For a properly loaded klystron; the output power for 2 or 1/2 times the optimum load (VSWR = 2) is still 85% of the maximum (-0.7 db). A 2:1 change of load conductance such as might occur with the injection of a proton beam would not be much of a disturbance.

No comparable data for a grounded grid triode is available.

#### Experience and History

The internal structures of a triode and a klystron have been compared, particularly with respect to the demands each makes on the emitter current capabilities and on voltage gradients within the tube.

In both respects, the klystron is much less demanding than is a triode.

The demands that the triode make on an emitter are particularly severe. The expected life of a thoriated tungsten emitter is given in Figure 2. The Figure is a re-drawing of Figure 1 of Reference 1, the Final Report on the A-2346. The values were computed by the authors of that report for strands carburized to a skin depth of 0.005".

The 7835, 2054 and A-15038 all operate at about 4 amperes/cm<sup>2</sup> peak emission density. From Figure 2, we see that the filamentary cathode must be operated near 2050°K to provide this much emission and that the expected life to exhaustion of the activated layer is about 15,000 hours.

Figure 2 also illustrates why, in this class tube, the life is so much a function of the application. If the tube is used where only 2 amperes/cm<sup>2</sup> is required, and the filament temperature is reduced to 1950°K, the expected life goes to 120,000 hours from 15,000 hours.

The significance of the emitter considerations is also borne out by the Air Force experience with the 7835.<sup>4</sup> It is used as the Final Amplifier in the FPS-24 Heavy Ground Radar Set in conditions that are almost identical with those needed for 1.25 Mw at 800 Mc, (i.e. 4 amperes/cm<sup>2</sup> current density, 250 kv/cm gradient in the plate circuit). In this service no tube had, as of March 1964, exceeded 6500 hours radiate time or 8500 hours filament time. The cause of failure, where it was clearly a tube fault, was in all cases due to cathode-grid shorts. These shorts are attributed to "shredding of the 96 interconnected thoriated-tungsten filaments in the 7835 which constitute the filamentary cathode".<sup>4</sup> The nearest related klystron experience is the VA-842 at 1.25 Mw, 75 kW at 425 Mc. One tube has recently attained 40,000 hours (2000 starts) and more than 40 have exceeded 20,000 hours.<sup>10</sup>

Although the maximum d-c voltage gradient in

the plate circuit is extremely high (250 kv/cm), this gradient does not seem to cause any difficulty in the 7835 in matched load operation. There is no d-c voltage on the output gap of the klystron. In it, the maximum d-c gradient is 53 kv/cm, in the cathode region.

Conclusion

We must conclude that, for equal quality of workmanship, a klystron has a much better chance of lasting a long time than a triode has. Furthermore, it costs one-third to one-half as much.<sup>4</sup>

References

- (1) Final Technical Report, RCA Development Type A-2346, RADC TDR-61-278, ASTIA-AD 274608
- (2) Final Technical Report; High-Power, Broad-Band, Coaxitron Amplifier; RADC-TR-60-94; ASTIA-AD 239275
- (3) Final Technical Report; High-Power, Broad-Band, Integral Cavity Coaxitron; RADC-TDR-61-315
- (4) Power Tube Digest, Report No. 1, ROAMA Power Tube Mgmt. Group, Hqs. ROAMA/RONUP, Griffiss AFB, N. Y., July 1964
- (5) A Comparison of Triodes and Klystrons for Particle Accelerator Applications, A. J. Morris and C. A. Martin-Vegue, (Presented at the Particle Accelerator Conference)
- (6) Transit-Time Effects in Ultra-High-Frequency Class-C Operation, W. G. Dow, Proc. IRE, P35, Jan. 1947

- (7) One-Kilowatt Tetrode for UHF Transmitters, W. P. Bennett and H. F. Kaznowski, Proc. IRE, P13, Jan. 1953
- (8) The Life of Barium Impregnated Cathodes, I. Brodie, Internal Memorandum
- (9) I. Brodie, R. O. Jenkins and W. G. Trodden; J. Electronics and Control, Vol. 6, P149, 1959
- (10) John Stapleton, BMEWS Project Engineer, Private Communication

Table I

|                      | Triode | Klystron |                      |
|----------------------|--------|----------|----------------------|
| $P_o$ - pk           | 1.25   | 1.25     | Megawatts            |
| $P_o$ - avg.         | 75     | 75       | Kilowatts            |
| P - Drive            | 125    | 1.25*    | Kilowatts            |
| $V_p$ or $V_{cath.}$ | +40    | -75      | Kilovolts            |
| $V_{coll.}$          |        | 0±5      | Kilovolts            |
| $I_p$ or $I_{coll.}$ | 80     | 40       | Amps. Peak           |
| $I_{body}$           |        | 2        | Amps. Peak           |
| $I_{grid}$           | 80     |          | Amps. Peak           |
| P-Heater             | 14     | 0.8      | Kilowatts            |
| P-Focus              | 0      | 1.5      | Kilowatts            |
| Coolant              | 50     | 2        | Gal./Min.            |
| Coolant              | 40     | 5        | Lbs./In <sup>2</sup> |

\* For 3 cavity tube, 63 watts for 4 cavity tube.

