

## THE AMPLITRON AS A HIGH POWER, EFFICIENT, RF POWER SOURCE FOR LONG PULSE, HIGH RESOLUTION LINEAR ACCELERATORS

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### Summary

An economical systems approach directed toward the generation of long pulse, high average rf power for linear accelerators can be achieved via the use of the Amplitron, an efficient crossed-field amplifier of high phase stability, in conjunction with a newly developed Machlett switch tube. A 3 Gc Amplitron to provide 3 mw peak power (150 kW average power) at 50  $\mu$ s pulse lengths is described. A cold secondary emission cathode of platinum is employed which enables a tube life of 10,000 hours to be guaranteed. Operating at a low anode voltage of 54 kV, the Amplitron is compatible with the ML-8549 super power switch tube; a hard tube modulator is thus employed. A single triode will switch a minimum of 10 Amplitrons. Not only is the cost of capital equipment drastically reduced by this unique, highly efficient combination of Amplitron-switch tube, but in addition, with grid control a fine adjustment on output power relative to the monitored beam energy can be made to achieve exceptionally high energy resolution in the beam.

### Introduction

The Amplitron, a high power crossed-field amplifier, is widely used in sophisticated pulsed radar where high phase stability is required.<sup>1</sup> Typical phase variation is approximately 0.2 - 0.4 degrees for 1%  $\Delta I_b/I_b$ . Its use as a power booster to enhance the output power by 10 - 13 db is occasioned by the high efficiency of the device. Efficiencies of 70% are typified by the QR849, a 400 kW (CW) S-Band Amplitron, while 75 - 80% efficiency has been obtained at 80  $\mu$ s pulse lengths, megawatt peak power, and 20 - 40 kW average power levels.<sup>2</sup>

The present high average power capability of the Amplitron is a direct result of a Government-supported program to develop crossed-field microwave tubes having an order of magnitude improvement in power generating capability.<sup>3</sup> A follow-on program dealing with life test and evaluation of super power Amplitrons is presently being carried out.<sup>4</sup> In addition, the performance of Amplitrons when operated at millisecond pulse lengths is being studied, and the high power frequency coverage from UHF through X-Band is being extended into the VHF range.<sup>5</sup>

The following paragraphs discuss various characteristics of the Amplitron which are of importance for linear accelerator applications and indicate a possible system approach directed toward achieving a high average power electron accelerator of high energy resolution.

### Phase Stability

The variety of radar systems in use today require exceptional phase stability and phase linearity. The wide acceptance of the Amplitron for use in these systems is therefore relevant.

The sensitivity of Amplitron to anode current variation is typically less than 0.4 $^\circ$  for a 1%  $\Delta I_b/I_b$ , a value which is comparable to that achievable with triodes. In contrast, the klystron will provide approximately a 10 $^\circ$  phase variation for a similar current variation. If a line-type modulator is employed to supply power to the Amplitron, then for small changes in load impedance, the modulator will deliver constant power. In terms of anode voltage a 1% increase in dc voltage will result in a 2% change in anode current or load power.

Measurements at L, S, and X-Band yield the following phase sensitivities:<sup>6, 7</sup>

Tube Type	Band	Power Output	Phase Sensitivity (degrees per 1% $\Delta I_b/I_b$ )
QK642	L	10 Mw	0.25
QK622	S	3 Mw	0.15
QK506	X	400-700 kW	0.3

The beam on-off phase shift has been measured for Amplitrons in a variety of frequency bands to lie between 10 and 25 $^\circ$ .

It may be of interest to note the phase linearity of the Amplitron, a factor of minor importance with regard to accelerators employing constant frequency rf sources:

Tube Type	Band	Measurement Bandwidth	Deviation from Linearity
QKS1012	L	100 Mc	3.5 degrees
QK622	S	150 Mc	4.0 degrees
QK506	X	50 Mc	1.2 degrees

### High Average Power Capability

The capability of the Amplitron to dissipate large quantities of CW or average power in the various tube elements is well illustrated by the successful development in late 1963 of the QR849, a 400 kW CW S-Band Amplitron. By the use of high velocity coolant flowing

through small channels, dissipation densities of 20 kW per cm<sup>2</sup> have been achieved, and values of 5 to 10 kW per cm<sup>2</sup> are typical in the S-Band CW tubes.

Due to its high thermal capacity, purified water having a resistivity of some 2-1/2 megohms has been found to be a satisfactory coolant. Typical flow is 100 feet per second at a pressure of 600 psi; bulk temperature rise of the water is only 20 - 25°C. Due to the high efficiency of the Amplitron, the pump power represents only a few percent of the total generated power.

Pulsed tubes operating at average power levels of 50 - 100 kW will have substantially reduced requirements on flow and pressure.

Another factor in achieving high average power is the development of suitable windows. For average power levels up to 100 kW, a now standard hemispherical ceramic window can be employed. At higher power levels, multiple windows are required, or special windows presently used for testing at the 1/2 Mw CW level could be employed if compatible with the system design.

#### Operating Life

Since the Amplitron was introduced in 1957, this device has been employed in a wide variety of radar systems, and consistent field return data on life is now becoming available. A typical example is the performance of tubes in the Federal Aeronautical Authority air route surveillance radars. This radar employs the 5 Mw L-Band QK653 Amplitron in over 50 sites. The average radiate life of these tubes in service has been 4700 hours while a number of individual tubes have clocked 10,000 to 13,000 hours.

The adaptation of a cold secondary emission cathode made from platinum by the Raytheon Super Power Operation for use in high power Amplitrons has removed the major cause for tube failure--the hot cathode.

The remarkable properties of the platinum cathode can be listed from which it can be seen that ultimate long life operation of crossed-field tubes may be greatly improved. These properties are the following:

1. Cold operation. With cold operation, the cathode is directly cooled with a liquid and is capable of withstanding very high bombardment power density for long periods of time. Its evaporation rate is comparatively low.
2. Freedom from poisoning. Because platinum is an inert element, it is not affected chemically by contaminants in the envelope or by gas or ions. It is, therefore, not susceptible to poisoning under relatively adverse operating conditions. It does not require any special processing or treatment as do hot cathodes.
3. It has a fairly high secondary emission ratio making it usable for a good many applications in crossed-field tubes to yield performance comparable to that of ordinary cathodes.
4. It is economical. Although platinum itself is an expensive material, its simplicity of construction

can offset this to a great extent so that the composite assembly is in general cheaper than a hot cathode. The present indications are that platinum can be successfully used as a plating on other materials such as copper and can thus be used in a minimum quantity.

CW Amplitrons for industrial heating applications rated at 50 - 100 kW, incorporate the platinum cathode and have a warranty for 10,000 hours. Pulsed tubes of comparable average power levels can be similarly guaranteed, while 20 Mw peak, 20 kW average power L-Band Amplitrons are rated at 20,000 hours.

#### Operation Into Mismatched Load

The Amplitron is unique in its bi-directional properties; a large mismatch at the output (accelerator cavity during buildup, for example) will reflect a large amount of power. In contrast to microwave tubes that employ cavity outputs such that the reverse power will be re-reflected at an improper phase toward the load, the Amplitron will transmit the reflected power to the input where it can be absorbed in the circulator load. Amplitrons typically operate into load mismatches of 2.5/1 VSWR of arbitrary phase.

An experiment has been performed to demonstrate the Amplitron can operate at high power directly into a section of accelerator guide without an intervening circulator. Stable operation was achieved at a power level up to 5.5 Mw (2.5 μs pulse, du = 0.0005) into a section of Stanford Accelerator guide. Testing at higher power levels was limited by arcing in a crossguide coupler located between the Amplitron and the accelerator section.

#### Application to Long Pulse, High Energy Resolution Linear Accelerators

The high average power capability of presently available Amplitrons can be utilized in linear accelerators for example where relatively low energy, high current machine of high energy resolution is desired. Assume an economical and reliable rf source is required to power a linear accelerator to provide a 300 Mev, 200 mA electron beam with a maximum duty cycle of 0.05 and a pulse length of 50 microseconds. An energy resolution of 1/10<sup>3</sup> - 1/10<sup>4</sup> is desired.

Assuming 5 meter cavities of shunt impedance similar to that obtained in the Stanford machine, the required rf power per cavity is 3 mw peak at 150 kW average to yield an energy of almost 11.5 Mev. An "on-the-shelf" rf system to satisfy the power, stability, and economic requirements incorporates a modified version of the S-Band QK622/8129 Amplitron, Figure 1, in conjunction with a hard tube modulator making use of the recently developed Machlett super power tube ML-8549.<sup>8</sup>

With the inclusion of high average power components in the QK622 Amplitron, the operating characteristics which can be conservatively met are:

Frequency	S-Band
Power	1.5 mw (peak) 75 kW (average)

Pulse Length	50 microseconds
Duty Cycle	0.05
Efficiency	70% (minimum)
Gain	13 db
Anode Voltage	54 kV
Life	10,000 hours
Phase Stability	$< 0.5^\circ$ for 1% $\Delta I_b/I_b$
Phase Change (power off - on)	$< 25^\circ$
Heater Power	none
Coolant	water, 10 gpm at 150 psi

To achieve 3 mw peak input power to each accelerator section, two Amplitrons are placed in parallel as shown in Figure 2. This approach of doubling or quadrupling the power is a standard procedure used in a number of successful high power radar systems. Magic Tees are used on both input and output. Note the Amplitrons are run from a common modulator, and balancing of the output power can be achieved by the use of a magnetic shunt across the individual tubes to adjust the operating point. Alternately a balancing resistor can be placed in series with the tube. The waste power delivered to the series arm of the magic tee can be held to under 0.5% of the output power.

Each Amplitron will have a dome-type high average power output window which has under test passed some 120 kW of CW power. A similar window can be inserted in the arms of the tee to provide a vacuum seal for the accelerator. A damping cavity coupled to the guide between the windows will eliminate any resonances which might be troublesome.

A single input window is employed; the Amplitrons are therefore packaged in a single vacuum envelope. There is a significant advantage to this arrangement over using separate input feed lines. In addition to a reduction by a factor of two of the number of circulators and input power couplers, the reliability of the input window is greatly enhanced due to the offset arrangement. The modular construction of the dual Amplitron package also permits simple replacement of any defective component. As a non-thermionic cathode is used, the Amplitron package can be let down to air, the defective component replaced, and the package immediately reprocessed without the usual costly cathode replacement.

The low operating voltage of the modified QK622 Amplitron makes a hard tube modulator system quite attractive from over-all system efficiency and economy considerations. A compatible and highly efficient switch tube is the Machlett ML-8549 super power triode. This tube is capable of delivering 60 Mw of power at pulse widths up to 10,000  $\mu$ s at a duty factor of 0.06. The anode dissipation is 500 kW at full power level. A single triode will switch a minimum of ten 3 Mw Amplitron packages.

The hard tube modulator approach minimizes the voltage droop problems encountered with pulse forming networks. While a thyratron line-type modulator will experience with great difficulty in generating 50 microsecond pulses with a pulse amplitude constant to 0.25%, the hard tube modulator with a proper grid compensation can be expected to provide a flat top voltage pulse

to within  $1/10^4$ . A possible system with grid control is shown in Figure 3. Note with grid control a fine adjustment on output power relative to the monitored beam energy can be obtained.

The above discussion has been related primarily to long pulse, high average power generation for low energy, high beam current linear accelerators. The family of Amplitrons is steadily increasing with present development work directed toward higher peak and average power. Future high power (either pulsed or CW) operation of accelerators will surely require the rf tubes and the accelerator to form a single vacuum envelope. Although yet to be demonstrated, this technique is definitely feasible as the Amplitron employs a cold platinum cathode. The gas pressure under normal operating conditions is maintained at  $10^{-7}$  to  $10^{-8}$  Torr; extended operation however at the 200 kW (CW) level at a pressure of  $10^{-6}$  indicates erosion of the cathode due to ion bombardment is minor and the tube life will not be significantly impaired.

Two other recent developments should be noted with regard to their future application to the accelerator area:

1. The development of lumped element rf circuits has resulted in the design of high power Amplitrons into the VHF range with 50 Mc being considered as the ultimate low frequency limit, and

2. An important recent breakthrough in Amplitron performance has been the laboratory demonstration of efficiencies of 85 - 90% at gain levels of 10 - 13 db. It is expected that the high efficiency techniques will be incorporated in future Amplitrons thereby achieving greater system economy and reliability.

#### References

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6. Clampitt, L., Huse, M. & Smith, W., "Measurement of Phase Characteristics of High Power Microwave Tubes," IEEE International Convention Record, Part 3, 1963, pp. 147-153.
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Figure 1. QK622 S-BAND AMPLITRON

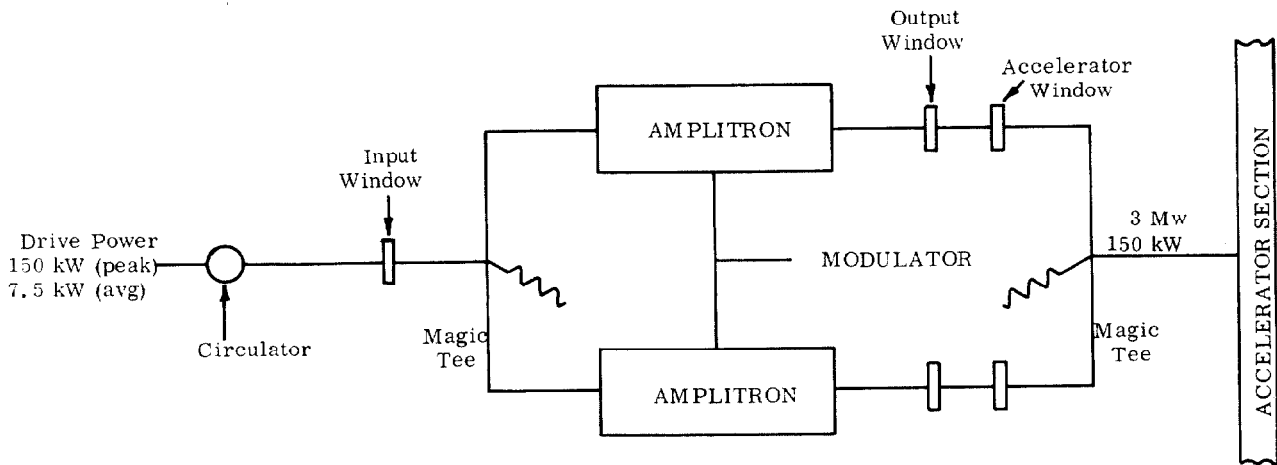


Figure 2. DUAL AMPLITRON PACKAGE  
 (3 Mw, 150 kW, 50  $\mu$ s, du = 0.05)

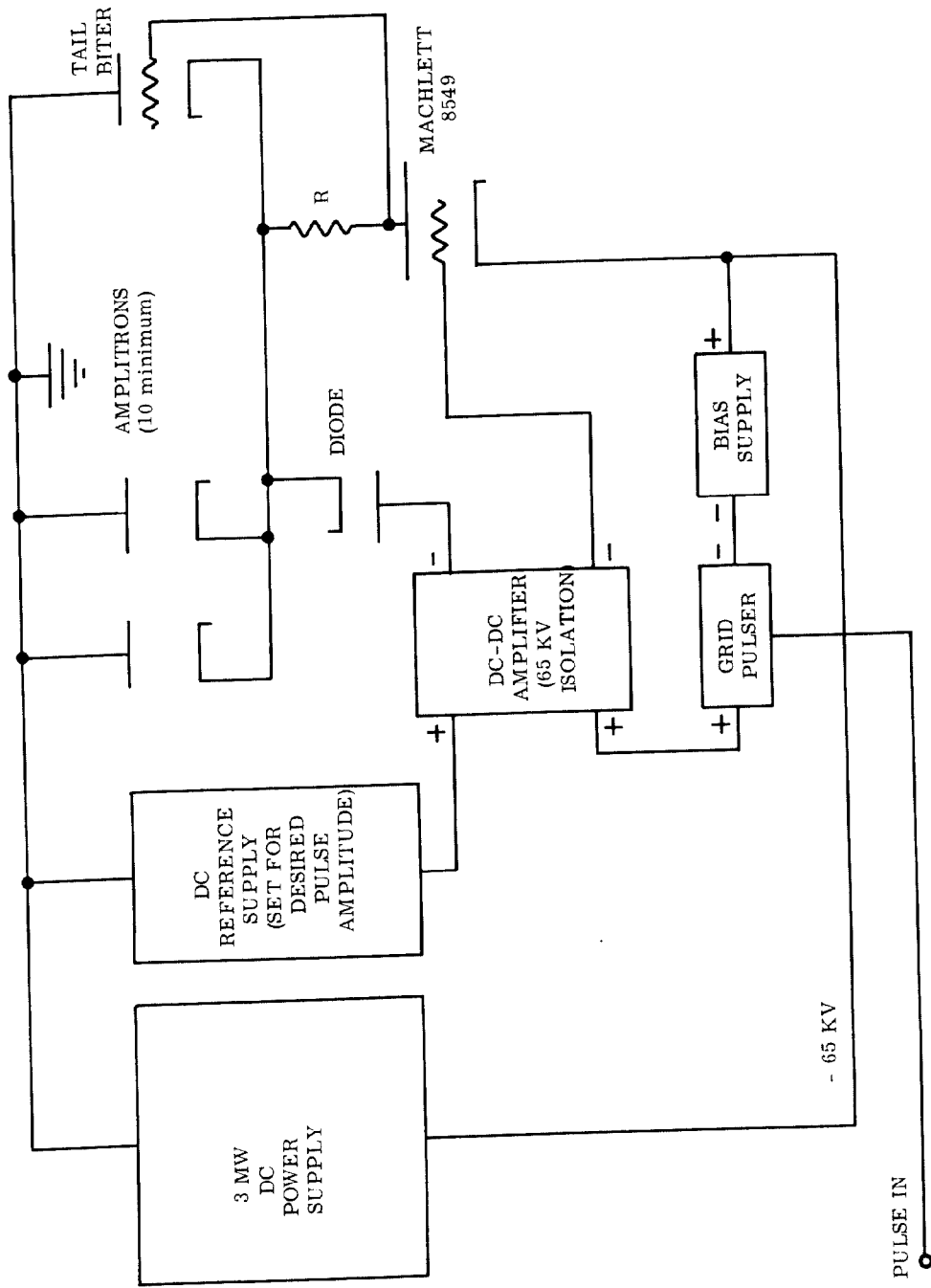


Figure 3. HARD TUBE MODULATOR SCHEMATIC (Burmac Electronics, Inc., Syosset, NY)