A COMPARISON OF TRIODES AND KLYSTRONS FOR PARTICLE ACCELERATOR APPLICATIONS

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Summary

In the frequency range between 200 and 1200 mcs, it is possible to use either klystrons or triodes for particle accelerator applications. This paper analyzes the bases of choice between these tube types from a systems point of view. It treats development status, initial and operating costs, reliability, system complexity, and all pertinent technical factors. The tentative specifications of the proton linear accelerator r-f system proposed by Los Alamos are used as a basis for comparison, and the conclusions reached on this system are extrapolated to higher and lower frequencies. It is concluded that either triodes or klystrons can be used in most, if not all, applications and that in almost every significant respect, in the frequency range considered, the klystron system is superior to the triode system.

Introduction

Particle accelerators operate with r-f drive sources at frequencies ranging from tens of megacycles to thousands of megacycles. At 200 mcs and below, where klystrons do not exist, all accelerators use triodes or tetrodes at peak powers up to 5 MW per tube. At 1200 mcs and above, where triodes (tetrodes) do not exist, all accelerators use klystrons at peak powers up to 30 MW per tube. At 476 mcs, the CEA synchrotron uses gridded tubes whereas the DESY synchrotron uses klystrons. In the frequency range from 200 to 1200 mcs, where both tube types exist, a comparison of their relative advantages in a major potential accelerator application seems useful. This comparison, if properly done, may serve as a guide in the design considerations of some of the new proposed machines. In making the comparison, one must consider all technical performance factors of the complete system along with development status, initial and operating costs, system complexity and reliability. To avoid generalities and to make the triode-klystron comparison most meaningful, we have chosen to use the tentative specifications of an 800 MEV proton linear accelerator proposed by the Los Alamos Scientific Laboratory (LASL) as a basis for comparison. The specifications used are dated April 3, 1964, and are:

Los Alamos Scientific Laboratory Specifications

Frequency	805 mcs fixed
Number of Amplifiers	50
Drive Power Available	5 Watts minimum average during pulse
Output Power	1.25 megawatts average per amplifier during pulse
Pulse Length	500 μs - 2 milliseconds
Duty Factor	6% maximum
PRF	30 pps fixed
Phase Control	±2° maximum deviation between accelerator cavity and master oscillator (10°/μs control rate)
Amplitude Control	±2% maximum deviation in accelerator cavity field relative to reference voltage

We will outline both a triode system and a klystron system, either of which would meet the LASL requirements. Neither of the systems are claimed to be optimized, but both will work and both include reasonable choices of system operating parameters. A key ingredient in both systems is the need for independent phase and amplitude control for each pair of accelerator cavities. Also, both systems must be capable of driving highly mismatched loads, must be designed to eliminate the possibility of window failure in event of high VSWR and must not be susceptible to damage during tube arcing from the energy stored in the accelerator cavities.

The Triode System

System Approach

In the LASL specification[1] is shown a block diagram of a 5 stage amplifier starting at the 5 watt input level. A simplification of this system is shown in Figure 1 which incorporates all of the remaining features which the authors believe essential to implement the system. The key ingredient in this approach is the RCA A15191 Coaxitron final amplifier, a version of which has been previously described and discussed[2]. RCA has issued a data sheet on this tube[3] which gives the pertinent parameters that have been used in the following analysis. The system shown in Figure 1 meets all of the LASL specifications. To get 1.25 MW peak power from the Coaxitron, it must be plate pulsed. Our switch tube choice for this is the Machlett ML-LPT14. This tube must pulse 76 amps peak current and its plate dissipation must include provision for ±5% line voltage variations, compensation for capacitor bank sag and the requirement to drop considerable additional voltage during the period that the r.f. output power required is less than peak. To get pulse amplitude stability and the desired waveform, a sample of the r.f. output is compared to a programmed waveform reference in a closed loop feedback system. This system is inherently capable of better than 0.1% amplitude regulation. A hard tube modulator being built by ENERGY SYSTEMS for the Brookhaven AGS Linac performs exactly the function required for the LASL system. This system has been described by Rheaume[4] and a very similar system is being implemented for the Argonne ZGS Linac[5]. For each 1 kv required drop in the system we pay in power:

1000 x 50 x 76 x 0.06 = 228,000 watts

For this reason, the system is designed to keep the drive to the final stage constant, to keep capacitor bank droop to 2 kv (5%) and to keep the size of crowbar resistors to a reasonable minimum, 10 ohms and 760 volts drop. Taking into account all factors, we get the required final plate supply voltage:

35,000	+ 1000	+ 2000	+ 2000	+ 2000	+ 2000
Coaxitron plate volts	Crowbar resistor drop	Capacitor droop	5% line voltage variation	Switch tube drop	Tube aging

$$= 44,000 \text{ volts}$$

The required power supply average current is:

$$50 \times 76 \times 0.06 = 228 \text{ amps}$$

We have shown this as a common power supply for 50 chains. This is well within the state of the art and represents a minimum cost-maximum reliability approach to the system. All other supplies were chosen as common supplies for this same reason. The required capacitor bank per Coaxitron is:

$$C = \frac{I\tau}{\Delta V} = \frac{76 \times 2 \times 10^{-3}}{2 \times 10^{3}} = 76 \ \mu f/80,000 \text{ joules}$$

(4 megajoules total for 50 chains)

None of the power supplies are electronically regulated. All are well filtered. All low voltage power supplies and filaments are fed from a common line voltage regulator. In order not to have to lose additional power in the final stage switch tube, we propose pulse regulating the drive to the final stage. This is done by a pulse regulator on the screen of the 6448 driver which compares its output against a drive amplitude reference. With this scheme, tube aging, transient and steady state line voltage variations and amplitude variations due to phase shifter variable attenuation with phase are all cancelled out during each pulse. These variations might total up to 50% but are easily compensated by screen control. For long filament life and to keep filament voltage ripple from appearing on the output pulse, a regulated d.c. filament supply is used on the Coaxitrons with provision for automatic filament run-up.

The driver capacitor bank is only 26 μf/5.2 KJ per tube and its energy can be discharged into a 100 ohm series resistor in event of a fault without a crowbar being required. R.F. phase control is obtained by sampling the r.f. voltage in one of the cavities and comparing it to a phase reference. The output of the phase comparator is amplified and used to control a ferrite phase shifter which can control at rates up to 10°/μs. The requirement of phase control to ±2° can be bettered by at least 10 times by this system. The triode phase sensitivity is about 1°/1% change in plate volts. The phase shifter is capable of a total phase shift of about 80°. When the accelerator cavity is filled and the proton beam injected, a 20-50% change in triode plate volts may be required to make up for beam losses resulting in a 20°-50° change in triode phase to be corrected; well within the phase shifter capability.

Table I shows the power consumption of the Figure 1 triode system. These numbers ignore the power requirements of the common drive stages which are negligible, but include the power requirements of a closed loop cooling system which incorporates its own heat exchangers. Based on Table I, the total predicted r.f. output/kva input system efficiency is 27%.

The cooling requirement of the triode system is about 6600 gpm at 45 psi, requiring 2 - 150 HP pumps and 4 - 50 HP fans.

In addition to normal protection against overcurrent, overvoltage, overtemperature, loss of flow, etc., the system is protected against tube arcs by crowbars and the Coaxitron output window would be protected against a waveguide arc by high speed arc detectors which operate on a low level r.f. diode switch to cut off the r.f. drive. The energy stored in the resonant cavities is less than 5 joules. If the Coaxitron arcs this r.f. stored energy is not sufficient to damage the tubes. The Coaxitron has a ceramic window. This must be located at a voltage null so that when the tube is operated into a short circuit the r.f. field at the window will be at a voltage minimum, not a voltage maximum. In fixed frequency systems, this is easily arranged. Since triodes are already successfully used in accelerator service, there is no question that they can be made to drive the load presented by the accelerator cavities.

Development Status

In the entire triode system there are only two items considered developmental in nature: the phase shifter and the Coaxitron. The phase shifter represents more of a design rather than a development problem. The Coaxitron is more developmental in nature. As of this writing, we believe a Coaxitron has been built which meets all system technical requirements. However, no life data or system experience exists on this tube type at close to LASL specifications.

Reliability

In discussing reliability we will discuss separately the final amplifier tube and the system as a whole. As will be seen later, this is not exactly a logical approach since overall reliability is much more a function of the rest of the system. What is really of interest for the final amplifier is the cost/operating hour as it is such an expensive device. In accelerator usage, triode life reports range from 10,000 to 25,000 hours. However, the statistical data available is very poor except from the military services. The military services issue an annual report[6], the results of which for the year 1 October 1963 - 30 September 1964 are shown in Table II. The Coaxitron is not listed in these results, but the 7835 Super-Power Triode and the 6950 are listed. The listing does not show the average life of all tubes in the field. It only shows the average life of the tubes that have failed during the period surveyed. It is of interest to note that of the tubes failed the

7835 shows an average life of 3960 hours at a cost per radiated/hour of $12.70 and that a tube operating at specifications roughly comparable to the proposed Coaxitron, the 6950, shows an average life of 5680 hours and a cost per radiated/hour of $5.34.

Table III is a tabulation of the overall expected failure rates of the triode system. These reliability estimates were made assuming a laboratory environment where MTBF is defined as the arithmetic average of the failure-free intervals. Only components whose values would result in inability of the system to perform its required function were used, and the assumption was made that all parts would be highly derated. Failure rate data were taken from standard references[8-12].

The calculated MTBF of the entire system of 33.3 hours is predicated on using a failure rate of 4.88 per million hours for all r.f. and high voltage tubes[8]. It is of interest to note that the part of the system contributing most to the low total MTBF number are the final amplifier modulators. Without these units the MTBF would be 114 hours.

Cost

Table IV shows a breakdown of the initial cost for the triode system. The total of $6,389,000 is intended to include all equipment, materials, design, construction and test costs; less shipping costs, electrical power contractor type installation costs and plumbing contractor type installation costs. Except for these, everything else is included. All numbers shown with the exception of the cost for the Coaxitrons include normal overhead, G&A and fee rates of ENERGY SYSTEMS. We assumed that LASL would purchase the final amplifier tubes directly from the tube manufacturer to avoid paying an additional markup. The price of $16,500 each for the Coaxitron has not been verified by RCA.

Table V is an operating cost breakdown for the triode system including only tube replacement and power costs. This total of $2,107,000 per year is seen to be a large fraction of the initial cost of the system. The cost of tube replacement is about 1-1/2 times the cost of power. The bases for the numbers shown are included in the table.

The Klystron System

System Approach

A klystron system which the authors believe is capable of meeting the LASL specifications is shown in Figure 2. The first amplifier stage runs as a cw amplifier at the 10 kw level. It uses a production tube, typically the Varian VA833C, which has a minimum gain of 40 db. Its beam supply is regulated to keep the r.f. output level within ±0.05 db. Two systems essentially identical to this, built by ENERGY SYSTEMS for SLAC, run at the 17.5 kw cw level at 430 mcs using Eimac klystrons. In the SLAC system the units are used almost identically with the way proposed here. Tubes of this type have averaged 10,000 hours life[6] in tropo scatter communications applications by the military.

The first amplifier output is split to drive 50 chains of klystrons through the same phase shifting system as in Figure 1. The peak power level in the phase shifter is down by a factor of over 20 from the triode system. The operational requirements are the same with the exception of the total phase shift required. The phase shifter is driven by a constant drive level and its output amplitude variation over the entire range of phase shift is 1 db. For the klystron, the expected variation of phase with 1 db drive amplitude change should be about 5°.

The klystron final amplifier we propose to use is an 805 mcs version of the BMEWS klystron. In the BMEWS system, at 430 mcs, klystrons built by Eimac, Litton and Varian have logged hundreds of thousands of hours of life at exactly the same power level, pulse length and duty cycle as the LASL specifications. Also, by simple scaling, Eimac has built a 1200 mcs version of the same tube.

In discussing beam supply and capacitor bank requirements, we are using BMEWS tube specifications. To meet the LASL specs a significantly lower beam voltage tube could be designed. The klystron has several characteristics which we are taking advantage of: (1) its 40 db minimum gain allows a greatly simplified drive chain; (2) it has a modulating anode, which is effectively a non-intercepting grid with a gain of two, allowing control of beam current and output power with low dissipation in the modulator tubes; (3) it allows phase control by merely stabilizing the body-cathode voltage even though the cathode-collector voltage is allowed to change appreciably.

Figure 3, an example of such a system, is a block diagram of a klystron transmitter developed by ENERGY SYSTEMS for the Air Force Automatic Swept Frequency Interferometer Radar System. As in the LASL system, phase linearity and phase stability are essential. To reduce the total stored energy required, separate collector and body banks are used with the body bank being recharged through a charging diode. Such a system allows 10% collector voltage sag while maintaining 2% or less body voltage sag. The body voltage sag can be corrected by an active body regulator handling at most 3% of the beam current. The modulator connections shown are also applicable to the LASL system.

Figure 2 shows a separate collector bank for each klystron and a common body bank with an active pulse body current regulator. The system voltage required is:

$$\underset{\substack{\text{Klystron}\\ \text{beam}\\ \text{volts}}}{\underline{100{,}000}} + \underset{\substack{\text{5\% line}\\ \text{voltage}\\ \text{variation}}}{\underline{5000}} + \underset{\substack{\text{body}\\ \text{bank}\\ \text{sag}}}{\underline{2000}} + \underset{\substack{\text{body}\\ \text{regulator}\\ \text{drop}}}{\underline{2000}} + \underset{\substack{\text{tube}\\ \text{aging}}}{\underline{5000}} + \underset{\substack{\text{crowbar}\\ \text{resistor}\\ \text{droop}}}{\underline{1000}}$$

$$= 115 \text{ kv}$$

The beam supply average current for 50 tubes is:

$$I_{avg} = 50 \times 0.06 \times 30 = 90 \text{ amps}$$

Each collector bank, assuming 12 kv allowable sag at 30 amps peak collector current per tube is:

4.9 μf/35,280 joules

The common body bank, assuming 2 kv allowable sag at 35 amps total peak body current is:

35 μf/252,500 joules

Total stored energy required is:

$$50 \times 35{,}280 + 252{,}500 = 2{,}016{,}500 \text{ joules}$$

In series with each collector bank are 2 - 20 ohm crowbar resistors which limit the energy into an arc to under 1 joule. The common body bank of 35 μf/252,500 joules has 2 - 10 ohm crowbar resistors which limit the energy into a body arc to about 5 joules.

The common body bank is feasible because each tube draws only 0.7 amps max. of pulse body current or a total of 35 amps for 50 tubes. One regulator tube can easily handle this pulse current and regulate the body voltage to 0.1%. This would result in under 1° of phase shift due to body voltage variations since:

$$\frac{\Delta\varphi}{\Delta V} \simeq 4.5° \text{ for } 1\% \; \Delta V$$

As in the triode system, we have a separate crowbar on each collector bank, and, in addition, we have a crowbar on the common body bank.

Figure 2 shows that output power amplitude control is achieved by controlling the modulating anode voltage with a separate floating deck modulator for each klystron using an amplitude waveform reference as in the triode system. Such a system was successfully built by ENERGY SYSTEMS years ago for experiments with the CEA 6 Bev Synchrotron cavities at 476 mcs. The phase shift to be expected by such mod anode control, for a 20-50% output power variation required due to accelerator cavity loading, is probably less than 15°. Therefore, the total expected phase variation to be corrected in the klystron system is about 20°, well within the 80° phase shift range of the phase shifters and comparing favorably to the phase shift correction required for the triode system.

All comments on system protection made for the triode system are equally applicable to the klystron system. The flow requirement for the klystron system is about 3,750 gpm at 50 psi, requiring smaller pumps and fans than for the triode system.

The klystron has a ceramic window, so does the triode. As pointed out by Merle Hoover of RCA[7], the solution to avoiding window failure is exactly the same for both tubes in this application. This leaves only one open technical consideration - can klystrons drive highly mismatched loads such as represented by proton linac or electron synchrotron cavities during the r.f. build-up time and prior to beam injection? They are doing exactly this in the DESY synchrotron application and did this in the early CEA experiments with klystrons by using an isolator. Lundstrom[13] treats this question and points out that for these applications an impedance transformer solves the problem in the same way that matching the triode amplifier to the load compensates for a fixed mismatch. In both cases, the output phase and amplitude depend only on the load - which is the same. Don Priest of Eimac has also treated this problem in private correspondence. His conclusions are the same. No isolator should be needed.

Development Status

As for the triode system, the phase shifters need development. While the exact klystron does not exist at 805 mcs, BMEWS versions of this tube do exist at both 430 mcs and 1250 mcs. To build an 805 mcs version of this same tube is a design - not a development job.

Reliability

We will again treat separately the final amplifier tube from the entire system. Table VII[6] shows for the VA842 BMEWS klystron an average life for 52 tubes failed during the year 1 Oct. 1963 - 30 Sept. 1964, of 6950 hours at a cost/radiated hour of $2.02. This tube operates at exactly LASL specs except for frequency. Table VIII is a tabulation of the overall expected failure rates of the klystron system. The same data as for the triode system were used. The calculated MTBF for this system comes out to be 73.2 hours.

Cost

Table IX shows an initial cost breakdown for the klystron system. Its total of $4,373,000 is based on exactly the same assumptions as for the triode system. For the klystron, our assumption of $13,000 per tube is based on the existence of at least 3 companies: Eimac, Litton and Varian; who have already built tubes of this type and have all of the necessary test equipment on hand. A production order of 430 mcs versions of this tube for the BMEWS system was priced at $13,700/tube.

The tube replacement and power operating costs for the klystron system are shown in Table X. For this case, the cost of power exceeds the tube replacement cost by about 15%. We have used $1.50/hour as the operating cost number for the klystron. We believe that klystrons to meet LASL specs will be available for rent at numbers not exceeding this.

Comparison Summary Klystron-Triode System

The preceding paragraphs have analyzed separately and in detail klystron and triode systems. To make a meaningful comparison, two tables have been prepared which summarize the relative cost and characteristics of the two systems and highlight the major areas of difference.

Table XI readily identifies the areas of cost difference in the two systems. In reviewing what makes the initial triode system cost almost 50% more than the klystron system, it is obvious that most of this difference is represented by the need for: (1) additional driver chains for the triode system; (2) higher power modulators for the triode system; (3) much higher energy storage for the triode system; and (4) a higher capacity cooling system for the triode system. The factors which make the operating cost of the triode system almost 50% more than for the klystron system are lower efficiency, higher tube cost and shorter tube life.

Table XII shows an overall comparison of two systems. This tabulation illustrates the marked advantages of the klystron system in terms of initial and operating costs and reliability.

Extrapolation to Other Frequencies

At frequencies above 800 mcs, klystrons have been built and are operating successfully at peak powers above 20 MW and average powers of 300 KW. Tubes with 60 MW peak power and 1 MW average power are being built. There is no question here of the preferred tube type. In the 400-600 mcs area, klystrons still appear to be the preferred choice. On BMEWS, for example, an 8 tube klystron system was chosen over a two tube triode system - even with the added complexity of combining the 8 tubes. For Nike-Zeus, klystrons were the tube of choice. At 200 mcs, the situation is different. Triodes do exist and have operated reliably at the 10 MW level. However, the problem of building 200 mcs klystrons is one only of mechanical design. The techniques for constructing such tubes exist.

For the triode, the Coaxitron represents an improvement by going to integral cavity design, eliminating r.f. contact problems and putting all high gradient fields inside a vacuum. A major improvement would be in the direction of increasing the tube hold-off voltage characteristics so that a plate modulator would not be needed. This would greatly increase system reliability. Efficiency decreases but probably is a trade off with the savings made by eliminating plate modulator losses. Costs are, of course, also reduced.

For the klystron many improvements are possible. Permanent magnet focussing is being used and can be incorporated into other klystron designs. Higher perveance guns would reduce beam voltage and oil-filled systems shouldn't be required. Higher gain mod anodes will permit all solid state modulators. With mod anode klystrons common modulators for many tubes are possible. Accelerator designers may not be able to take advantage of this but it should be included in their thinking. Finally, higher efficiency is very much in the offing. Efficiencies of 40% are now typical and 50-60% is being achieved.

Conclusions

The results of our analysis and comparison of both triode and klystron systems to meet the LASL specifications clearly and conclusively favor the klystron approach. It is less expensive initially, cheaper to operate, simpler, more reliable, more efficient and in every way meets the system technical requirements. In the area of amplitude control and stability and phase control and stability, both the triode and the klystron system can easily be made to exceed spec requirements. For systems at frequencies higher than 800 mcs the klystron looks even better. At frequencies of 400 mcs and 600 mcs the military have chosen klystrons over triodes in big ground systems. At 200 mcs, where triodes exist and klystrons do not, we would still choose the klystron if the system were large enough to absorb the design cost of the first tube.

Perhaps the most significant conclusion which can be drawn from our analysis is that it pinpoints the biggest single area of weakness in the triode approach, the need for high level plate modulators. Eliminate these and the triode-klystron gap narrows appreciably. However, the advantages of the klystron are tough to overcome. The combination of high gain, phase control by controlling low current cathode-body potential only, and non-intercepting electrode beam control are features not achievable in gridded tubes.

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TABLE I

POWER CONSUMPTION BUDGET FOR PROPOSED TRIODE SYSTEM
(Total Watts for 50 Chains)

	3rd	4th	5th	6th (Driver)	7th (Final)	Modulator	Total
Filaments	◄——	4,400	——►	135,000	665,000	123,000	927,000
Grids	◄——	500	———	——►	---	13,500	14,000
Screens	◄——	8,000	———	——►	---	---	8,000
Plates	◄——	20,000	——►	700,000	8,208,000	1,824,000	10,752,000
Cooling							450,000
						TOTAL	12,151,000

TABLE II

TRIODE/TETRODE FIELD LIFE DATA

Failures in the year 1 Oct. 1963 - 30 Sept. 1964

Tube Type	Description	Operating Parameters	No. Failed	Average Life (Hrs.)	Cost/Radiated Hour (Dollars)
7835	Super-Power Triode	5 MW/.06 Du/ 2000 μs/250 mcs	22	3960	12.70
6950	Shield Grid Triode	1.5 MW/.05 Du/ 2000 μs/200 mcs	29	5680	5.34
A-2054	Super-Power Triode	5 MW/.06 Du/ 2000 μs/250 mcs	4	4260	14.10
A-4616/2669	Triode		6	900	17.70
6952	Tetrode	2 MW/.004 Du/ 13 μs/425 mcs	47	1790	5.68
2041/A2515	Inside Out Tetrode	2 MW/200 mcs	44	7300	.74
7214	Tetrode	65 KW/.01 Du/ 10 μs/1215 mcs	79	2660	.15

TABLE III

MTBF OF FIGURE 1 TRIODE RF SYSTEM

Part or Assembly	Total Adjusted F_R
Power Supplies	
(1) 8 Low Voltage Supplies	10
(2) 10 MW Power Supply	17
(3) .7 MW Power Supply	17
Screen Pulsers 53 units	262
Final Amplifier Modulators 50 units	21,240
DC Regulated Filament Supplies 50 units	40
Phase Detector and Amplifier Circuits 50 units	546
Cooling System - Flow Manifolds 50 units	593
Capacitor Banks 100 units	300
Crowbars 50 units	38
RF Tubes and Associated Equipment	6,680
Miscellaneous Items	305
Grand Total Adjusted F_R	30,048

$$\text{MTBF} = \frac{10^6}{\sum_0^N F_R} = \frac{10^6}{30,048} = 33.3 \text{ hours}$$

TABLE IV

INITIAL COST BREAKDOWN FOR FIGURE 1 TRIODE RF SYSTEM

Item	Description	Price
1	Development (New Components)	20,000
2	System Design and Integration	200,000
3	Installation and Test	860,000
4	Common, Low Level, Driver Chain	80,000
5	Common, Low Voltage, Power Supplies	25,000
6	6448 Plate Supply and Capacitor Bank	100,000
7	Final Amplifier Plate Supply and Capacitor Bank	690,000
8	Final Amplifier Plate Supply Crowbars	150,000
9	Final Amplifier Pulse Modulators	1,000,000
10	Final Amplifier Filament Supplies	100,000
11	Final Amplifier Magnet Supplies	Not Required
12	Final Amplifier Tubes at $16,500 each	825,000
13	Final Amplifier Focussing Magnet	Not Required
14	Final Amplifier R.F. Plumbing and Dummy Loads	220,000
15	Final Amplifier Lead Shielding	Not Required
16	Driver Chain(s) Including Phase Shifter	1,350,000
17	Control Console and Installation Materials	115,000
18	Cooling System Including Flow Manifolds	554,000
19	Miscellaneous Materials	100,000
	Total Price	$6,389,000

TABLE V

OPERATING COST BREAKDOWN FOR FIGURE 1 TRIODE SYSTEM*

(Tube Replacement and Power Cost Only)

TUBE REPLACEMENT COSTS:

Tube Type	Notes	Estimated Average Life (hrs.)	No. Tubes	Cost/Hr./ Tube	Total Cost/ Year
A15191	Hours Based on Data for 6950(8) Cost Based on $16,500 per Tube	5,680	50	$1.98	$ 823,000
6448	Hours Based on Data for 2041(8)	7,300	50	$0.74	308,000
7651	Hours Based on Data for 7214(8)	2,660	55	$0.09	41,000
ML/LPT-14	Hours Estimated, Conservatively	7,500	50	$0.25	105,000
		Total Tube Replacement Cost/Year			$ 1,277,000

POWER COST:

$$\frac{12,151}{\text{KW}} \times \frac{1}{\begin{array}{c}0.85\\ \text{Power}\\ \text{Factor}\end{array}} \times \frac{8,320}{\text{Hours Per Year}} \times \frac{\$.007}{\begin{array}{c}\text{Dollars Per}\\ \text{KVA Hours}\end{array}} = \$\ 830,000$$

Total Tube Replacement and Power Cost $ 2,107,000

* Based on 8,320 Hours
Per Year Operation

TABLE VI

POWER CONSUMPTION BUDGET FOR PROPOSED KLYSTRON SYSTEM

(Total Watts for 50 Chains)

STAGES

	Driver	Final	Modulator	Total
Filaments	200	37,500	15,300	53,000
Magnets	2,000	175,000	---	177,000
Cathode-Collector	35,000	10,031,000	50,000	10,116,000
Cathodes-Body	---	250,000	---	250,000
Cooling	---	---	---	300,000
			TOTAL	10,896,000

TABLE VII

KLYSTRON FIELD LIFE DATA

Failures in the year 1 Oct. 1963 - 30 Sept. 1964

Tube Type	Description	Operating Parameters	No. Failed	Average Life (Hrs.)	Cost/Radiated Hour (Dollars)
VA842	Klystron	1.25 MW/.06 Du/ 2000 μs/425 mcs	52	6,950	$ 2.02
L-3035	Klystron	2.2 MW/.003 Du/ 8 μs/1250 mcs	55	8,920	.60
VA87 ( )	Klystron	2 MW/.001 Du/ 6 μs/2800 mcs	113	3,500	1.09
SAC42A	Klystron	3 MW/5 kmc	101	3,490	1.54
L-3250	Klystron	10 MW/.002 Du/ 7 μs/1300 mcs	59	3,050	3.79
L-3403	Klystron	1.25 MW/.06 Du/ 2000 μs/425 mcs	64	3,250	5.87
Z-5010	Klystron	10 MW/.002 Du/ 7 μs/1300 mcs	29	3,540	6.78
ZM-3038A	Klystron	15 MW/.003 Du/ 15 μs/2800 mcs	21	1,033	29.80
3KM3000LA	Klystron	2 KW/CW/385-585 mcs	4	19,020	.11
3KM50,000PA	Klystron	20 KW/CW/225-400mcs	87	4,700	3.60
4KMP10,000LF	Klystron	400 KW/.01 Du/ 60 μs/600 mcs	14	4,550	4.55
4KM50,000 LQ/LR	Klystron	10 KW/CW/610-985mcs	36	10,000	.33

TABLE VIII

MTBF OF FIGURE 2 KLYSTRON RF SYSTEM

Parts or Assembly	Total Adjusted F_R
10 MW Power Supply	17
10 KW Common Driver	431
Final Amplifier Modulators 50 units	9,050
Phase Detector and Amplifier Circuits 50 units	546
Cooling System - Flow Manifolds 50 units	593
Capacitor Banks 50 units	175
Crowbars 50 units	37
R.F. Final Amplifier and Associated Equipment	2,340
Magnet Supplies 150 units	180
Miscellaneous Items	305
Grand Total Adjusted F_R	13,674

$$\text{MTBF} = \frac{10^6}{\sum_0^N F_R} = \frac{10^6}{13,674} = 73.2 \text{ hours}$$

TABLE IX

INITIAL COST BREAKDOWN FOR FIGURE 2 KLYSTRON SYSTEM

Item	Description	Price
1	Development (New Components)	20,000
2	System Design and Integration	200,000
3	Installation and Test	760,000
4	Common, Low Level, Driver Chain	80,000
5	Common, Low Voltage, Power Supplies	Not Required
6	6448 Plate Supply and Capacitor Bank	Not Required
7	Final Amplifier Plate Supply and Capacitor Bank	460,000
8	Final Amplifier Plate Supply Crowbars	200,000
9	Final Amplifier Pulse Modulators	700,000
10	Final Amplifier Filament Supplies	25,000
11	Final Amplifier Magnet Supplies	60,000
12	Final Amplifier Tubes	650,000
13	Final Amplifier Focusing Magnet	200,000
14	Final Amplifier R.F. Plumbing and Dummy Loads	220,000
15	Final Amplifier Lead Shielding	50,000
16	Driver Chain(s) including Phase Shifter	150,000
17	Control Console and Installation Materials	115,000
18	Cooling System including Flow Manifolds	383,000
19	Miscellaneous Materials	100,000
	Total Price	$4,373,000

TABLE X

OPERATING COST BREAKDOWN FOR FIGURE 2 KLYSTRON SYSTEM*

(Tube Replacement and Power Cost Only)

TUBE REPLACEMENT COSTS:

Tube Type	Notes	Estimated Average Life (hrs.)	No. Tubes	Cost/Hr/ Tube	Total Cost/ Year
Finals & Driver		---	51	$1.50	$636,000
Mod. Switch Tubes	Mod. Switch Tube Hours Estimated Mod. Switch Tube Cost Based on $250 Per Tube	7,500	100	$0.033	27,500
	Total Tube Replacement Cost				$ 663,500

POWER COST:

$$\frac{10{,}896}{\text{KW}} \times \frac{1}{0.85\ \text{Power Factor}} \times \frac{8{,}320}{\text{Hours Per Year}} \times \frac{\$.007}{\text{Dollars Per KVA Hours}} = \$\ 748{,}000$$

Total Tube Replacement and Power Cost $1,411,500

* Based on 8,320 Hours Per Year Operation

TABLE XI

COST COMPARISON-TRIODE SYSTEM AND KLYSTRON SYSTEM

ITEM	TRIODE	KLYSTRON	DIFFERENCE
1. Design, Development, Installation Test	$1,080,000	$ 980,000	$ +100,000
2. Power Supplies, Capacitors, Switch Gear	965,000	660,000	+305,000
3. High Level Modulators	1,000,000	700,000	+300,000
4. Final Tube Filament and Magnet Supplies	100,000	85,000	+ 15,000
5. Final Amplifier Assembly Including Tubes, Magnets, Lead Shielding and R-F Plumbing	1,045,000	1,120,000	- 75,000
6. Common Low Level Driver Chain	80,000	80,000	0
7. Driver Chains (50)	1,350,000	150,000	+1,200,000
8. Control Console, Installation Materials and Miscellaneous	215,000	215,000	0
9. Cooling System	554,000	383,000	+171,000
TOTAL INITIAL COST	$6,389,000	$4,373,000	+$2,016,000
Power Operating Cost Per Year	$ 830,000	$ 748,000	$ + 82,000
Tube Replacement Cost Per Year	1,277,000	663,500	+613,500
TOTAL COST PER YEAR	$2,107,000	$1,411,500	+$ 695,500

TABLE XII

OVERALL COMPARISON OF KLYSTRON AND TRIODE SYSTEMS

ITEM	TRIODE SYSTEM	KLYSTRON SYSTEM
Initial Cost	$6,389,000	$4,373,000
Operating Cost/Year	2,107,000	1,411,500
Final Amplifier Life (Hrs.)	5,680	6,950
System Reliability (MTBF Hrs)	33.3	73.2
Power Consumption (Watts)	12,151,000	10,896,000
System Efficiency	27%	30%
Energy Storage (megajoules)	4	2
Cooling	6600 gpm/ 45 psi	3750gpm/ 50 psi

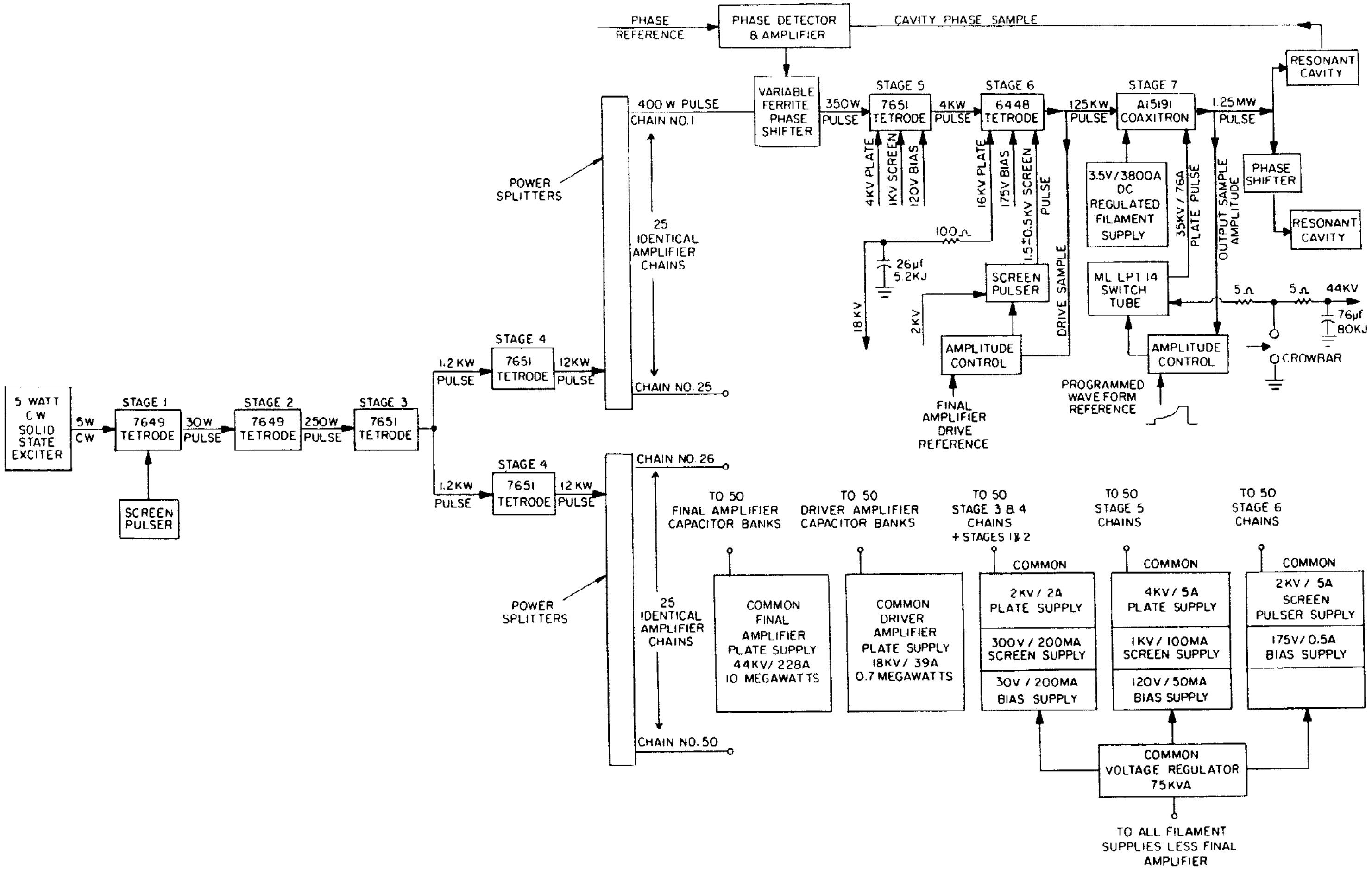

Fig. 1. ENERGY SYSTEMS Proposed Triode RF System for Los Alamos Scientific Laboratories Proton Linear Accelerator.

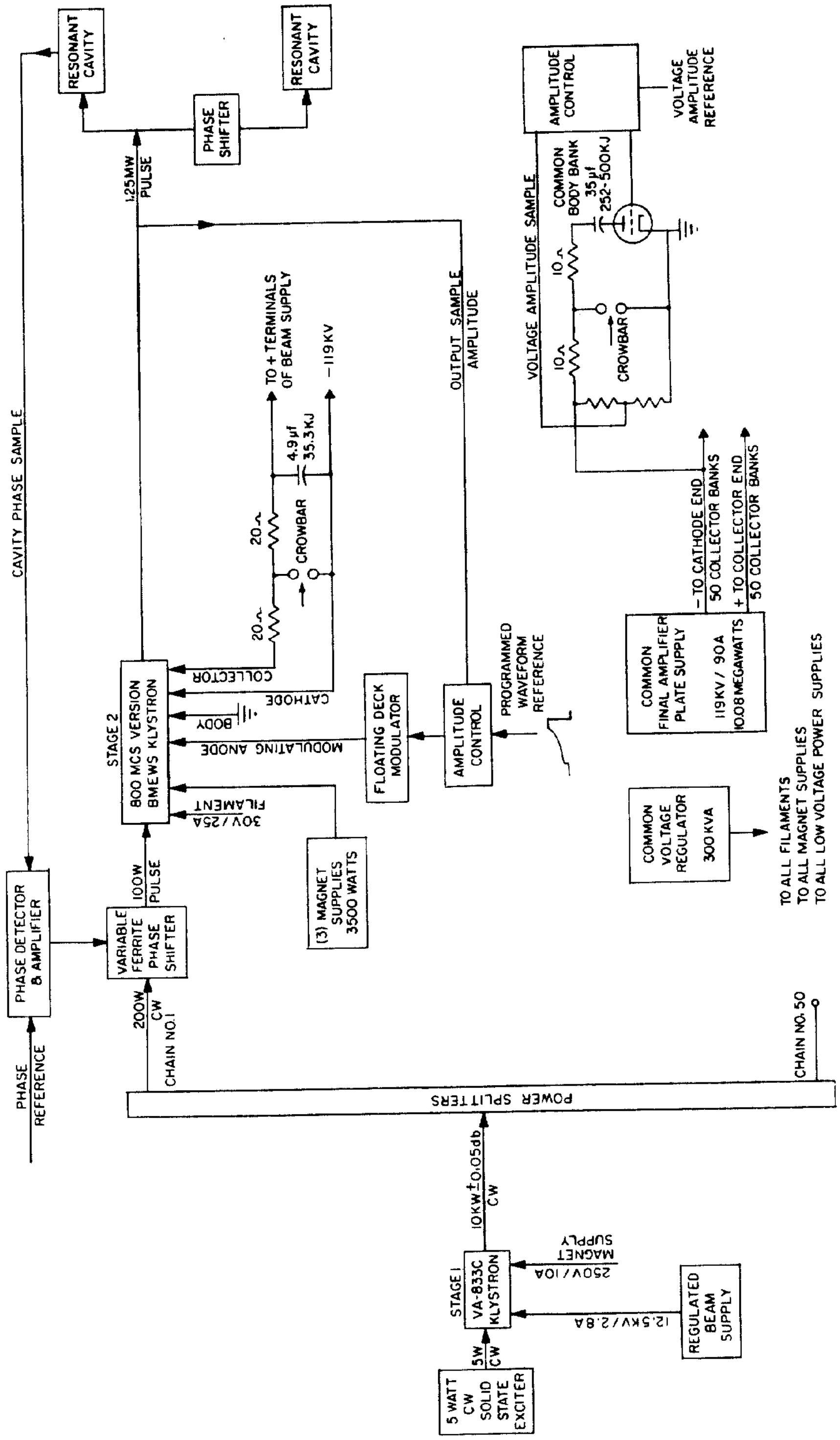

Fig. 2. ENERGY SYSTEMS Proposed Klystron RF System for Los Alamos Scientific Laboratories Proton Linear Accelerator

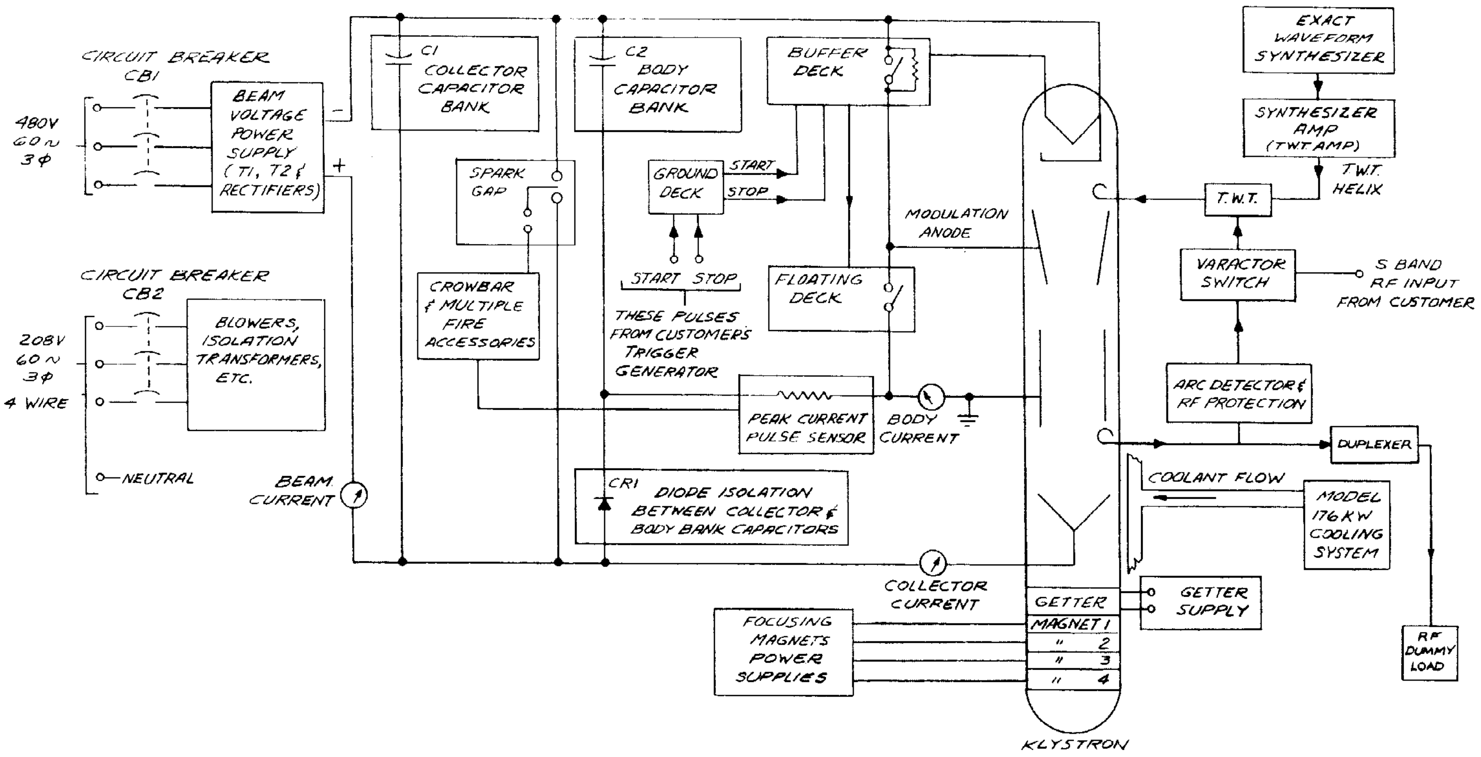

Fig. 3. Simplified Block Diagram of a Phase Stabilized Radar Transmitter