HIGH DUTY FACTOR RF SOURCES AT 800 MHz*

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Summary

The proton linear accelerator for the Los Alamos Meson Physics Facility will require 45 one-megawatt, 800-MHz rf power sources. The minimum duty factor requirement is 6% (500 μs pulse 120 c/s); eventually, a 12% duty factor (1000 μs pulse 120 c/s) will be needed. The accelerator structure which is the load for the amplifier has a high Q (typically between 20,000 and 30,000); the amplifier loading is further complicated by a variable beam load which may absorb as much as 30% of the amplifier output. Triodes, klystrons, and crossed-field amplifiers all show promise for this service. The Los Alamos Scientific Laboratory is testing and comparatively evaluating these three rf systems. The systems are described in this paper and a discussion of the evaluation program is given.

Introduction

The choice of an rf amplifier system for the highly specialized purpose of powering a proton linac is complicated by many considerations; these range from effects on the beam dynamics caused by errors in the rf power source to the capital cost of the system. In this paper, a discussion of the major considerations is given; it is based on design work at the Los Alamos Scientific Laboratory for an accelerator to be used as a meson factory.[1] The next section of the paper gives a description of the electrical character of the load presented by the accelerator. The following section presents a discussion of the three most promising rf systems including a report of our experience with them. The final sections of the paper discuss the basis for comparison of rf systems and the comparative costs.

The Nature of the Load

The characteristics of the slow-wave accelerator structure and the accelerated beam play a dominant role in determining the requirements on the operational characteristics of the power amplifiers. Hence, before a detailed discussion of the amplifiers is begun, it is pertinent to review briefly the accelerator characteristics. The parameters discussed are those of the accelerator for the Los Alamos Meson Physics Facility. The slow-wave structure parameters are representative of the state-of-the-art development in this field and the beam parameters are typical of heavy beam loading.

The individual accelerating cavities[2] operate in the TM_{010} mode and are shaped for optimum efficiency. Inter-cavity coupling is accomplished by separate coupling cavities placed along side of the accelerating cavities. Typically, about 75 accelerating cavities are coupled together to form an accelerator tank. Each accelerator tank is operated in the resonant π/2 mode and is accurately tuned to a frequency of 805 MHz. A dispersion curve for this structure is shown in Fig. 1. The curve is a discrete series of points (whose number is equal to the total number of cells) since the structure is operated resonantly (standing wave) rather than as a traveling wave structure. At the π/2 mode, the group velocity is at its maximum value; this results in a uniform energy density along the tank even under heavy beam loading and contributes greatly to the electrical stability of the accelerating fields. The shunt impedance and Q values are shown in Fig. 2 as a function of particle energy.

The transient response of such a device has been studied on the basis of a chain of coupled resonant circuits and the results in some cases have been experimentally verified.[3,4,5] The general effect is that, at the start of a pulse, the tank presents an infinite mismatch to the generator (VSWR = ∞). During the filling time, a beating phenomenon occurs between the mode at the drive frequency and its near neighbors on the dispersion curve. As the tank approaches its equilibrium condition, the beating dies away. The time scale is related to the Q values of the driven mode and its neighbors ($\tau \sim 2Q/\omega$). Since the Q values are large, the e-folding times for field buildup and changes in mismatch are long (~ 10 μs). The variation in impedance as a function of time is shown in Fig. 3 for a typical case. The exact trajectory on the impedance plane depends on the slope of the dispersion curve, the separation of adjacent modes, and the Q values.

The beam loading will be approximately 30%;** the exact value depending on the shunt impedance. Beam dynamics studies have shown that, in order to maintain reasonable beam loss through the accelerator, the accelerating fields must be controlled to an amplitude accuracy of ± 1% and a phase tolerance of ± 1°. The beam current is sent through the accelerator at a phase angle of 26° leading the peak electric field; thus, the beam loading is reactive as well as resistive.

The time sequence of any pulse is that, first, the power sources are switched on for the entire accelerator and the accelerating fields are brought to the requisite value. The beam is then turned on and the power amplifier output is continuously adjusted to maintain the desired fields independent of loading.

The overall length of a particular accelerating tank determines the power requirement and it is

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** Beam loading is that fraction of the power delivered to the accelerator converted into kinetic energy of the beam.

possible to adjust this length so that all of the amplifiers operate at the same power level.

Based on the above and other considerations, the operating specifications for the amplifiers are shown in Table I. A total of 45 amplifiers are required.

Table I
AMPLIFIER OPERATING SPECIFICATIONS FOR LAMPF

Peak power output	1.0 MW (full beam loading)
Average power output	60 kW (120 kW)*
Load mismatch	∞ at start of each pulse 1.5 (no beam loading) < 1.1 (full beam loading)
Overall gain of amplifier system	60 dB
Phase control	± 1°
Amplitude control	± 1%
Bandwidth	± 2 MHz minimum (this is wide enough so that the accelerator bandwidth is the dominant rf bandwidth)
Operating frequency	805 MHz
Duty factor	6% (12%)
Pulse length	500 μs (1000 μs)

The reliability is of primary importance since in proton linacs (unlike the electron linacs) all of the rf systems must be consecutively operational along the linac from the injector to the station at the desired proton energy. Thus, if any rf system fails, it precludes production of a proton beam at energies higher than those available in the accelerator at the region of the failed rf system. Since the reliability is such an important consideration, the amplifiers are to be constructed with a 25% safety factor in power output, i.e., the amplifiers will be able to deliver 1.25-MW peak power and stay within all ratings.

Different Amplifier Systems

In this section, the three types of amplifier systems under active study are discussed. For each, a general description of the main components and an abbreviated schematic diagram is given. In all cases the system is described in terms of the eventual 12% duty factor operation. Following the general description, a summary of our experimental work is given.[6]

In the three systems, the drive signal is supplied at the one-watt level. Phase and amplitude correction signals are generated by comparing the fields measured in the accelerator tank with suitable references.[7] These correction signals provide the primary method of regulating the accelerating fields. Some open-loop amplitude correction may also be obtained by properly choosing the length of the transmission line between the final amplifier and the accelerator tank.[8]

* Initially, the machine will be operated at 6% duty factor but eventually a 12% duty factor will be necessary.

The Triode - Klystron System

System Description. A schematic of this system is given in Fig. 4; the first 50 dB of rf amplification is provided by a klystron and the final 10-12 dB by a triode amplifier. Klystrons of this sort are similar in many respects to those currently in use in UHF TV service and are well developed; it is likely that for this service a specially designed narrow-band tube would be produced to maximize efficiency and reliability. The triode is one developed by RCA (called a coaxitron) and employs coaxial input and output circuitry constructed as an integral portion of the tube structure. A photograph of an 805-MHz coaxitron is shown in Fig. 5; the operating specifications are given in Table II.

Table II
OPERATING SPECIFICATIONS OF
THE PRESENT RCA 805-MHz COAXITRON

Power output	1.25 MW
Anode voltage (maximum)	40 kV
Conversion efficiency** (minimum)	37%
Gain (minimum)	11 dB
Duty factor	6%
Cooling water (maximum)	55 gal/min
Filament power	3300 A at 2.7 V

Modulation of the klystron driver is provided by a pair of triodes which control the potential of the klystron modulating anode; these are arranged so that the klystron is either completely on or completely off. The circuit is so arranged that the slump of the capacitor bank changes only the potential of the collector and not the kinetic energy of the electron beam, thus, minimizing phase shift during the pulse.

Phase control is achieved by the use of a fast phase shifter at low level. Varactor phase shifters[7] have been developed and are suitable for this service.

Amplitude control is obtained by varying the anode potential of the triode by use of a floating deck modulator. Suitable modulators have been developed using the Machlett 8618 magnetically focussed triode.[9,10] It appears that other tubes, such as the EIMAC 4CW100,000D, may also be suitable for this service. Such a scheme of amplitude control maintains the rf efficiency of the amplifier at a nearly constant value over any reasonable variation in the required output power; however, the overall system efficiency is decreased at lower output powers since the drop across the modulator tube is increased.

Operating Experience. We have used the triode-klystron system for a variety of experiments and measurements during the past two years. Typical results of measurements of the most important transfer characteristics of the coaxitron are as follows:

$$\frac{\Delta P_o}{\Delta V} = 50 \text{ W/V}$$

** Conversion efficiency is defined as the ratio of the total rf output to the input from the modulator.

$$\frac{\Delta\phi}{\Delta V} = 4 \times 10^{-3} \text{ deg/V}$$

$$\frac{\Delta I}{\Delta V} = 1 \times 10^{-3} \text{ A/V}$$

where P_o is the rf output; ϕ, the phase shift across the tube; and V, the anode voltage. The phase and amplitude noise during the pulse are satisfactory.

A Rieke diagram (by which we mean a plot of the tube output and efficiency as a function of the complex load impedance) has been measured for the presently operating tube and this shows that the tank circuit coupling and/or tank circuit resonant frequency is improperly adjusted. For example, a typical anode efficiency is 33%; yet, it appears that, if the load impedance were properly adjusted, this could be as high as 45%. Calculations predict an efficiency of 45-50%.[11]

Operation into a resonant load has been successfully demonstrated and a coaxitron is now being used to power a standing-wave electron accelerator.

The principal difficulty associated with this tube has been connected with attempts to operate at 6% duty factor; as yet, 6% duty factor operation has not been demonstrated with a useful life. Since the tube structure is an appreciable element in the resonant cavity forming the plate tank circuit, its dimensions must scale with the wavelength; this has the consequence that the power dissipation densities within the tube are high. Other tubes have been successfully run at equivalent dissipation densities, but the design must be well developed to accomplish this. To date, successful operation at 3% duty factor has been achieved and the 6% duty factor operation should be demonstrated within the next few months. Judging from the present experience, we believe a 12% duty factor coaxitron will require a substantial development effort.

The Klystron System

System Description. A schematic of this system is shown in Fig. 6. The main amplifier is a klystron similar to those developed for radar service. Such a tube typically has an rf gain of 50 dB, an efficiency of 40%, and is switched by a modulating anode. The collector is electrically isolated from the tube body.

Phase control is achieved by a fast phase shifter (such as the varactor device mentioned above) at the one-watt level. An important feature in minimizing the variation in phase shift across the klystron is the arrangement of the modulator circuit. The kinetic energy of the beam is determined by the potential difference between the cathode and the tube body; the body current is low and so this potential may be highly regulated without a large capacitor bank and high-current regulating elements.

Amplitude control is provided by a drive modulator inserted in the driveline to the klystron. This drive modulator also provides the first 10 dB of rf gain. This type of modulation means that the klystron runs at lower efficiency during any portion of the pulse when the required rf output is below normal.

Two klystrons suitable for this system are being built by Litton and testing of the first tube should start in April of 1967 at the Los Alamos Scientific Laboratory.

The specifications of the Litton klystron are shown in Table III; a sketch of the tube is shown in Fig. 7.

Table III
OPERATING SPECIFICATIONS OF THE LITTON KLYSTRON

Power output	1.25 MW
Cathode voltage (maximum)	-78 kV
Conversion efficiency (minimum)	40%
Gain (minimum)	50 dB
Duty factor	12%
Filament power	13 A at 30 V
Cooling water	102 gal/min
Magnet power	6 kW

Operating Experience. All of our experience with klystrons to date has been with the EIMAC 4KM70LH-1 which we have used both as an rf driver for amplifier tubes and as a power source for short sections of accelerator.

Measurement of a Rieke diagram has shown that this klystron is well behaved over a reasonable range of load mismatch. Further, experiments in which high Q resonant loads were driven have demonstrated the practicality of klystrons for this type of service.

Results of the more important transfer characteristic measurements are:

$$\frac{\Delta P_o}{\Delta V} = 5 \text{ W/V}$$

$$\frac{\Delta\phi}{\Delta V} = 2.5 \times 10^{-2} \text{ deg/V}$$

$$\frac{\Delta P_o}{\Delta P_{in}} = 10^{5}$$

$$\frac{\Delta\phi}{\Delta V_M} = 3.6 \times 10^{-3} \text{ deg/V}$$

where P_o is the rf output power; ϕ, the phase shift across the tube; P_{in}, the drive power; I, the beam current; and V_M, the modulating anode voltage. The transfer characteristics of the 1.25-MW tube will be different; but, we do not anticipate unmanageable values.

The Crossed-Field Amplifier - Klystron System

System Description. A schematic of this system is shown in Fig. 8. The first 50 dB of rf gain is provided by a klystron (similar to that used in the triode-klystron system) and the final 10 dB by a crossed-field amplifier (CFA).

As with the other systems, phase control is achieved by use of a fast phase shifter at low levels coupled with appropriate feedback circuitry.

The amplitude control shown employs a series modulator to regulate the cathode voltage of the CFA. Another possible scheme is to amplitude-modulate the drive (as in the klystron system) and use the series modulator simply to regulate the cathode voltage. The same modulator is used to drive the cathode of the driver klystron. A tetrode modulator tube is shown (such as the EIMAC 4CW100,000D); the Machlett 8618 could also be used.

A unique feature of the CFA's is that, while the tube amplifies in the forward direction, it also transmits power in the backward direction with very little attenuation (< 1 dB). Thus, such a tube is prone to oscillation if there is any mismatch in the output line and the input line is not back-terminated. To prevent this oscillation, an isolator is used between the klystron driver and the CFA. This isolator will see large reflected powers during the transient at the beginning of the pulse and must be designed accordingly.

Two CFA's suitable for this service are being built for us by Raytheon to the specifications shown in Table IV. These Raytheon tubes (called Amplitrons) are being built in a cascade arrangement of two Amplitrons within a single vacuum envelope. Electrically, the tube is constructed so that the two cathodes are connected in parallel while the rf circuitry is connected in series. The cathodes are of the secondary emission type and do not require heaters. The magnets are permanent. A photograph of one of these tubes during assembly is shown in Fig. 9.

Table IV
OPERATING SPECIFICATIONS OF THE RAYTHEON AMPLITRON

Power output	1.25 MW
Cathode voltage (maximum)	50 kV
Conversion efficiency* (minimum)	70%
Gain (minimum)	11 dB
Cooling water	20 gal/min

Operating Experience. We have used small 805-MHz Amplitrons (QKS1461) for a variety of experiments and measurements since May of 1966. These tubes were designed to operate at 100-kW output power either CW or peak. No difficulty has been encountered with power dissipation problems.

Using the two available tubes, we have assembled a cascade amplifier which is electrically similar to the 1.25-MW tube. The pertinent transfer characteristics of this cascade arrangement are as follows:

$$\frac{\Delta P}{\Delta I} = 2.1 \times 10^{4} \text{ W/A}$$

$$\frac{\Delta \phi}{\Delta I} = 2.4 \text{ deg/A}$$

$$\frac{\Delta I}{\Delta V} = 1.2 \times 10^{-2} \text{ A/V}$$

$$\frac{\Delta P}{\Delta P_{in}} = 2$$

where P is the output power; I, the total Amplitron cathode current; ϕ, the phase shift across the two Amplitrons; and P_{in}, the drive power from the klystron. This cascade arrangement has produced peak powers as high as 475 kW with efficiencies in excess of 60%. The gain of the two Amplitrons ranged from 2-9 dB and the operating voltage was ~ 32 kV.

* Conversion efficiency in this case is defined as the ratio of the difference between output power and drive power to the input power.

Difficulty has been encountered in this cascade arrangement with oscillations at frequencies other than the operating frequency. These oscillations have been caused by improper design of the slow-wave structure and transitions between it and the drive and output waveguides. The situation is confused by the discovery that, due to a brazing misadventure during construction, one of the tubes has had a cathode with only 1/3 of the design area usable. We have succeeded in eliminating the oscillations in most cases by the following techniques:

a. The use of an isolator in the driveline.

b. Reduction of the electron beam coupling to fields at spurious frequencies within the tube by perturbation of the magnetic field. This technique unfortunately degrades performance at 805 MHz.

c. Adjustment of the phase and magnitude of load mismatch.

By exploiting these techniques, we have succeeded in demonstrating successful operation of the cascade Amplitron driving a resonant load. It appears that amplitude and phase noise are satisfactory. In a properly designed tube, the need for magnetic shimming or load tuning should be obviated.

A disadvantage of the CFA is its low dynamic impedance. While awkward, this does not appear to make amplitude control of the output via control of cathode potential impossible. We have experimentally verified that combination of the klystron modulator and CFA modulator in one unit as shown in Fig. 8 is feasible.

Comparison of the Amplifier Systems

It is a simple matter to compare the different systems we have studied on the basis of overall efficiency, cooling requirements, building requirements, and other similar system considerations but this really begs the more fundamental questions. The fundamental questions may be reduced, at some risk of over-simplification, to the following two issues:

a. Will the system work in this application?

b. What is the reliability?

By the first question we mean, can the proper electromagnetic field be achieved and controlled in the accelerator without undue complexity of the control system? All of our work thus far indicates that any of the three systems will provide an answer on this issue. However, before a firm answer can be provided, the appropriate measurements must be made on the full power systems. If all goes well, we should be able to resolve this issue within the next few months.

It should be clear that a measurement of system reliability is impossible to attain within the limitations of available time and money. Thus, we are forced to rely on our judgement and on past experience with rf systems similar in nature.

It appears that the major criteria for system reliability are:

a. Avoidance of components which operate near the limits of present materials technology.

b. Minimization of the number of components subject to failure by proper system design.

c. Conservative choice of component rating.

d. Wherever possible, use components of previously established reliability.

Of these, the fourth is the most powerful but unfortunately it cannot be directly applied to the most critical component in the system--the final rf power amplifier. It is true that power tubes of the type under consideration have established good reliability records once the tube design is well developed; we anticipate that such a development of design will also be necessary in this case.

Once the fundamental questions about the rf systems have been resolved within the framework of the above discussion and, if two or more of the systems are strongly competitive, we shall make a more detailed study of the secondary system design considerations. At that time, we should be in an excellent position to make our final system choice.

Costs

It is not the purpose of this paper to present a detailed cost schedule for the possible systems. However, it is germane to discuss briefly the relative capital equipment and power costs. In capital costs, it is obvious that the triode is most expensive since it is the least efficient and it requires a separate 100-kW driver. The klystron is less costly and the CFA is the least costly. The difference in cost between the klystron and CFA is small (< 10%) while the difference between the klystron and the triode is somewhat larger (~ 20%).

That portion of the operating cost due to power consumption again ranks the systems in the same order. The portion of the operating cost due to tube replacement is unknown since accurate tube lifetimes are unknown. The question of tube lifetimes has often been discussed;[12,13] unfortunately, definitive values are unknown and will remain unknown for this application until the system is operational and a statistically significant sample has been accumulated.

It must be emphasized that, while the question of cost is important and must be weighed in a system choice, it is not the most important criterion. Rather, in a specialized application such as the one under discussion, much more weight must be placed on those aspects of system choice relating to optimum performance.

Acknowledgements

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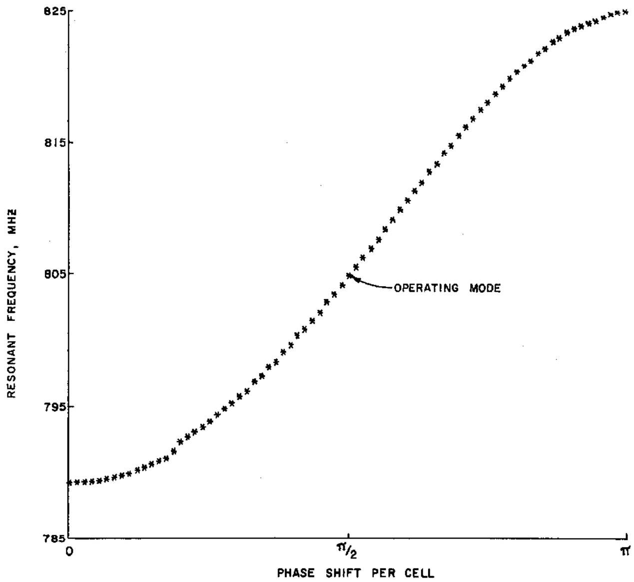

Fig. 1. The dispersion distribution for a typical section of the proton accelerator structure.

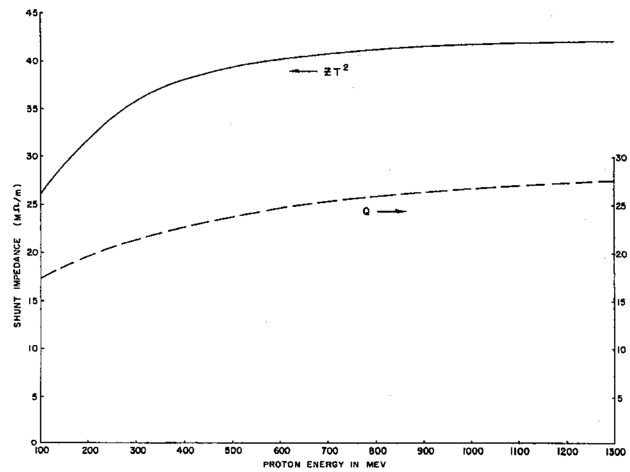

Fig. 2. The shunt impedance and Q of the accelerator structure as a function of proton energy.

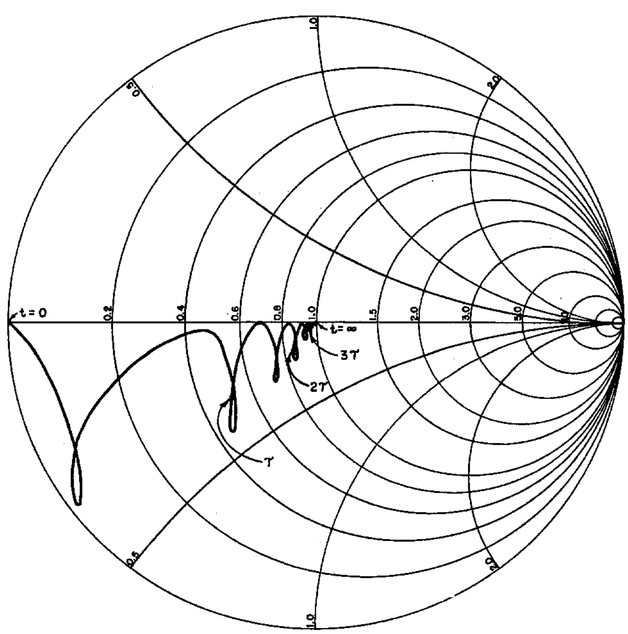

Fig. 3. The transient impedance of a typical resonant accelerator tank; τ is $2Q/\omega$.

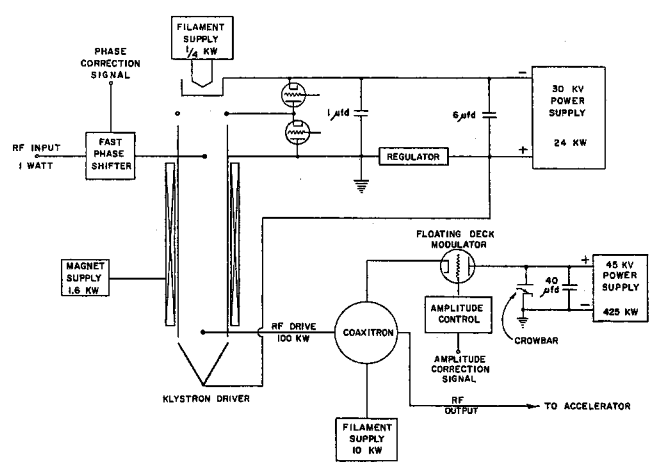

Fig. 4. The triode-klystron rf amplifier system with power supplies sized for 12% duty factor.

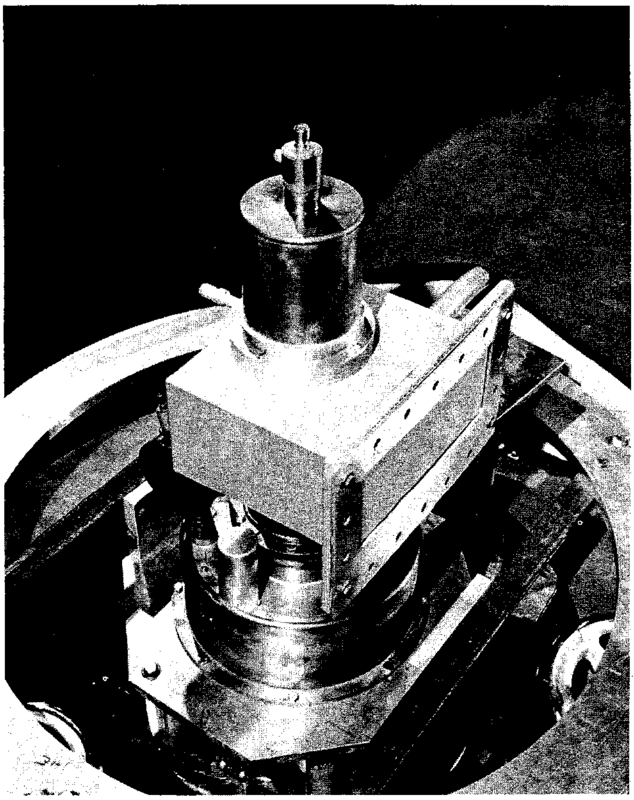

Fig. 5. RCA coaxitron used as the final amplifier stage in the triode-klystron system. The active region of the tube is in the cylindrical cavity below the output waveguide; filament, drive and anode connections are at the bottom of the tube.

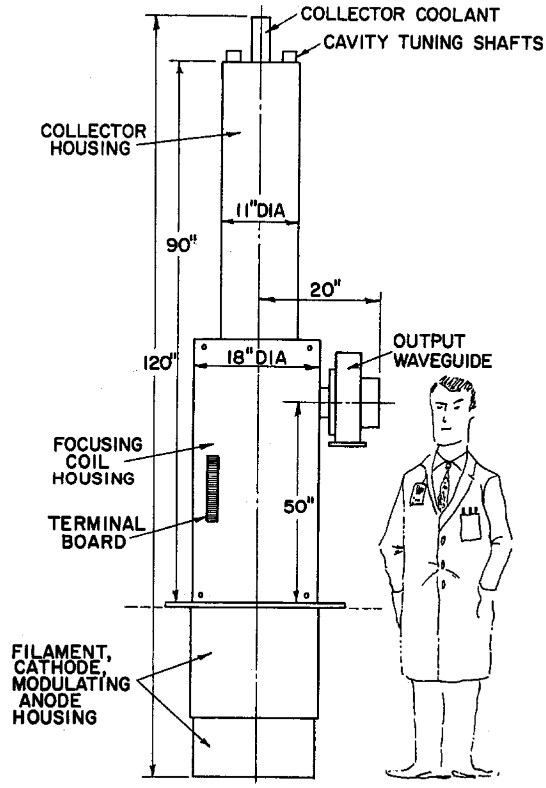

Fig. 7. A sketch of the Litton 1.25-MW klystron.

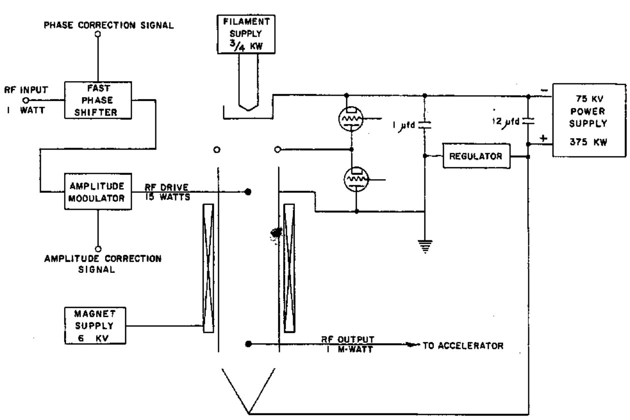

Fig. 6. The klystron rf amplifier system with power supplies sized for 12% duty factor operation.

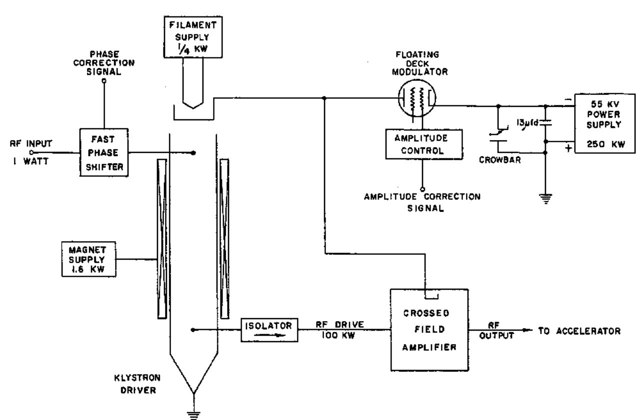

Fig. 8. The crossed-field amplifier—klystron system with power supplies sized for 12% duty factor.

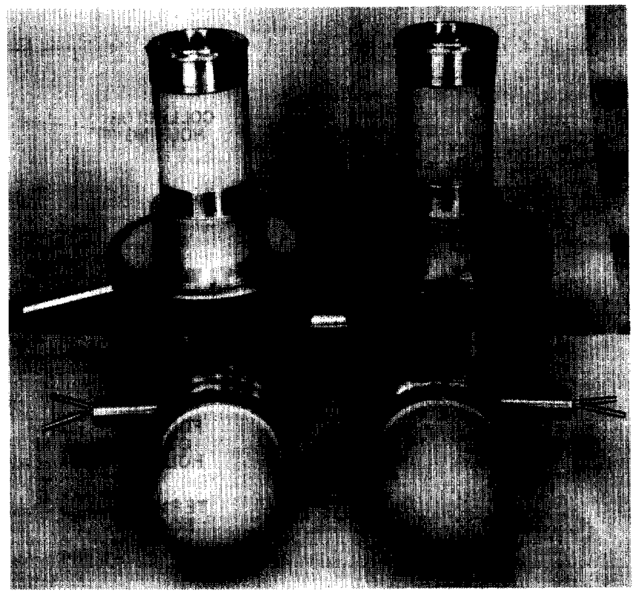

Fig. 9. The Raytheon Amplitron (a crossed-field amplifier) during assembly. The cathode connections are through the vertical bushings and the rf input and output are through the dome windows in the foreground.