805 MHz RF POWER SOURCES*

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Introduction

The LASL linac design calls for a 201.25 MHz Alvarez linac followed by waveguide tanks operating at 805 MHz. There are to be 45 amplifiers with 1 MW output at 805 MHz. This talk concerns these amplifiers, with emphasis on the final power amplifier tube: Table I gives the main specifications.

The rf field in the cavities must be held to 1% and 1° during the beam pulse, which will be done by a fast phase and amplitude servo control system. The servo operates on the error signals obtained by comparing the phase and amplitude of the field in the tank (accelerating section) with the phase and amplitude of a master driveline. The comparison is made at the power level of a watt or less. A system requirement on the final power amplifier therefore is that it have suitable control characteristics.

While the tank is being filled, or if there is a spark in the tanks or the feed lines, the final amplifier sees a bad mismatch. The tube must be able to withstand this condition repeatedly.

Other desirable operational characteristics of the amplifier are high anode efficiency, long lifetime, low fault rate, rapid recovery from faults, and ease of maintenance. General system requirements include simplicity and low capital cost.

Table I

RF Power Amplifier Specifications

Frequency	805.0 MHz
Bandwidth	± 2 MHz
Pulse Length	500 (1000) μs
Repetition Rate	120 cps
Duty Factor	6% (12%)
Power Output	1.0 MW

Three types of final amplifier tubes have been advocated for this service: triodes, klystrons, and crossed-field types; each has its advantages and its disadvantages.[1] Los Alamos has been carrying on a program of evaluating all three: it appears in the initial tests that all three are promising. We now discuss each type, and will summarize our experimental tests.

Crossed-Field Amplifier

The crossed-field amplifier for our service may be considered as a descendant of the cavity magnetron. A general reference is Okress.[2] Most of the major tube manufacturers offer crossed-field devices. The particular device we have evaluated in detail is the Amplitron, manufactured by the Raytheon Company, and this is the one we shall discuss, although its virtues and faults are not necessarily representative of all crossed-field amplifiers.

Figure 1 illustrates the Amplitron circuit. The dc magnetic field is perpendicular to the plane of paper, the dc electric field is radial. The electrons are produced by secondary emission from a platinum cathode. The E x B drift velocity of the electrons is azimuthal. The resonant structure, represented by the series of numbered circles, has a fundamental pass band such that an rf wave travels backward from output to input, with amplitude decreasing toward the input. The wave bunches the electrons, forming a rotating spoked wheel of charge; in this case there are four spokes. Figure 2 shows a computer plot of the electron motions, showing the motion of the spokes. The interaction of the bunched beam with the resonant structure converts drift kinetic energy into rf energy. The Amplitron in principle can have a high efficiency since the electron beam can recirculate through the interaction region. In practice, efficiencies up to 85% are reported.

An Amplitron will transmit a signal within its pass band with little attenuation in either the forward or backward direction. If the load is mismatched, a reflected wave will be sent back to the driver. Reflections can also make the Amplitron oscillate if the loop gain GBr_1r_2 exceeds unity, where G is the forward gain, B the backward transmission, r_1 and r_2 the reflection coefficients at arbitrary planes in the input and output. This consideration enters into the design of the input and output circuits, and implies that the Amplitron must be protected from loss of drive. An isolator is inserted to protect the driver and to prevent oscillations in the Amplitron.

Figure 3 shows an assembled 100-kW cw Amplitron, the QKS1461 which we tested at Los Alamos during May and June 1966, and Fig. 4 shows the parts before assembly. The parameters are cw output 100 kW, frequency 805 MHz, nominal gain 10 dB, and efficiency 60-70%.

One successful circuit configuration used in the tests consisted of a 100-kW driver, followed by a 3-dB resistive attenuator, the Amplitron, an isolator, and finally the load. A second successful system employed the isolator between driver and the Amplitron rather than the output. It was found necessary to suppress an oscillation at 750 MHz. The oscillation suppressor was a series of waveguide sections and a water load, which at 750 MHz loaded the output heavily, but at 805 MHz very little. Amplitrons to be delivered in the

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future will embody internal suppression of this oscillation. Figures 5,6, and 7 show curves characteristic of the best operation of this tube, and Figs. 8-9 show scope traces of the pulsed operation. The parameters corresponding to Figs. (8-9) were

4.8 A
26 KV
7 dB
110 kW total output power
efficiency = 70%

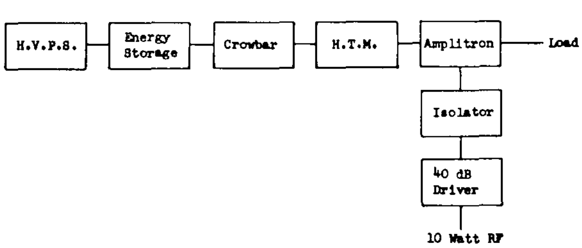
Figure 10 displays the pulse of the rf in a wave-guide tank being driven by the Amplitron. The circuit lineup was klystron driver → isolator → Amplitron → oscillation suppressor → cavity load. The cavity load was our model B 20 cell cloverleaf tank. The Amplitron pulse is 250 μs, the driver klystron pulse overlaps this pulse at the beginning and the end. The drive power feeding throuth the Amplitron produced the pedestals at the beginning and end of the pulse. The very fast wiggles on the leading and trailing edge of the pulse are the transient excitation of other cavity modes. Some people have expressed concern about the performance of Amplitrons into resonant loads. The above test demonstrates that the Amplitron can drive satisfactorily a resonant waveguide tank.

A second 100-kW crossed-field amplifier (Amplitron) is being fabricated by Raytheon. Although basically identical to the first model, the tube will incorporate a few changes suggested by the experience gained in testing the first. It will be subjected to an even more exhaustive test program than the first.

In view of the encouraging results attained with the 100-kW Amplitron, specifications were prepared for a crossed-field amplifier having the following principal characteristics:

Peak power output	1.25 MW
RF pulse length	1000 μsec
Pulse repetition rate	120 pps
Gain	11 dB
Efficiency	70%
Anode voltage	50 kV
Average power output	150 kW

A contract for procurement of two tubes is being negotiated with Raytheon, and the tubes are being fabricated. A test stand is being built in the Mockup Building. The system looks as follows:



Triode

The triode final power amplifier which we have tested is the RCA developmental type A15191, called by RCA the coaxitron. It employs built-in coaxial resonant circuits in the plate and grid, hence the name. It is designed to operate as a grounded grid amplifier. The design parameters were as follows:

Frequency	805 ± 2 MHz
Output power	1.25 MW
Duty factor	6%
Gain	11 dB
Filament current	3500 A
Filament voltage	2.5 V
Plate voltage(max)	40 KV
Plate Current	90 A

The output section matches into WR975 waveguide and the input is 1-5/8" coax line. Figures 11 and 12 show the components and the operating schematic for the coaxitron. Figure 13 is a LASL computation of the rf field inside the tube. We have been testing these tubes at LASL for over two years, studying the following characteristics:

a) gain, efficiency, noise level, peak power
b) lifetime
c) performance into resonant loads
d) control characteristics, both open loop and closed loop

The arrangement for testing is shown in Fig. 14. Curves of output power and efficiency are shown in Figs. 15 and 16, for a pure resistive load. The plate efficiency is about 37%, and the gain 11-12 dB. Performance has been satisfactory except for lifetime under 6% duty and 1 MW operation. The causes of failures have been various; many arising from difficulties in fabrication and assembly, but some, such as anode failure, requiring redesign of portions of the coaxitron. The CEA experience with coaxitron lifetime, however, has been excellent. We have contracted with RCA to purchase two tubes redesigned to the following specifications:

Peak power	1.25 MW
Gain	11 dB min
Duty factor	6%
Pulse length	666 μs
Efficiency	37% min
Grid driveline	3-1/8 in. o.d.
Output	crunch seal coupler to WR975 W.G.

Delivery is expected by this winter. A 3% duty coaxitron has operated satisfactorily in our laboratory for several months.

Klystron

Advantages of the klystron are its high gain (eliminates the need for an intermediate power amplifier (IPA)), reasonable plate efficiency (40-45%), and a relatively simple and rugged collector design. Output window failure, which has been a problem with high power S-band klystrons, should be much less of a problem with 1 megawatt L band klystrons.

The Eimac model 4KM70LH klystron has been operated here since 1965 for testing accelerator components and as a driver. Originally designed as a cw power amplifier for TV service, it was redesigned by Eimac to deliver 100 kW peak, 6 kW average power at 805 MHz. The maximum gain is 50 dB. We have had several in service during the last 18 months; operating experience has been good. Only one failure occurred, when, because of an operator's mistake, an excessive standing wave ratio developed on the output line causing a window failure: this tube was repaired. Tests were completed to determine both the dynamic and steady state characteristics. Steady state measurements determined power output and phase difference between input and output as a function of power supply voltage, rf power input, frequency, and focusing magnet current. Figure 17 shows the output power versus input power (drive) and versus beam voltage, and Fig. 18 shows phase shift versus drive and beam voltage. Since this klystron has four tuned cavities, the results are dependent on the particular tuning. When the tube is tuned for maximum power output under the condition of drive saturation, typical characteristics are as follows:

1. $\frac{\Delta \text{ Power Output}}{\Delta \text{ Power Supply Volts}} \approx \frac{5 \text{ kW peak}}{\text{kW}}$ near 30 kV

2. $\frac{\Delta \text{ Power Output}}{\Delta \text{ Power Input}} \approx 0$ near drive saturation

3. $\frac{\Delta \text{ Phase Shift}}{\Delta \text{ Power Supply Volts}} \approx \frac{25^\circ}{\text{kV}}$, drive saturated

4. $\frac{\Delta \text{ Phase Shift}}{\Delta \text{ Power Input}} \approx \frac{5^\circ}{\text{W}}$, near drive saturation at 30 kV

5. Saturating Drive required for Max. Power Output at 30 kV ≈ 2.75 W

6. Bandwidth, 3 dB -2 MHz, +3 MHz

7. $\frac{\Delta \text{ Phase Shift}}{\Delta \text{ Magnet Current}} = \frac{\Delta\phi \text{ deg}}{\Delta i, \text{ A}}$

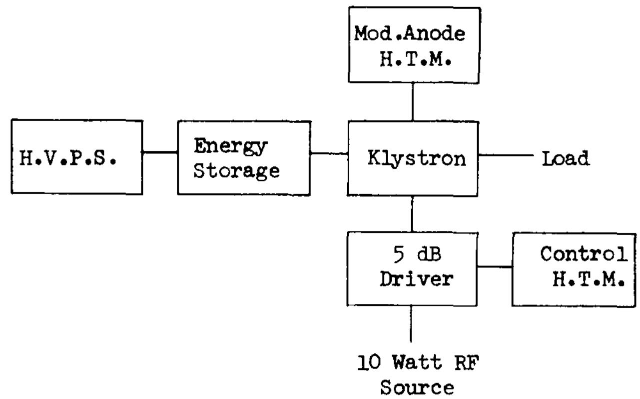
   $\Delta\phi \approx 8\ (\Delta i)^2$, centered at recommended magnet current - 16A

Open loop frequency responses of the klystron rf chain were taken for both phase modulation (klystron drive saturated) and rf drive amplitude modulation. The transient responses to pulse modulation of the same types were also observed. These data will be used to study AM-PM conversion and for control loop design.

Litton Industries at present are building two klystrons for LASL to the following specifications:

Frequency	805 MHz
Peak power output	1.25 MW
RF pulse length	1000 μs
Pulse rep. rate	120 Hz
Gain	50 dB
Efficiency	40%
Beam voltage	75 kV
Beam current	41 A
Average power output	150 kW

The tube will use solenoids for magnetic focusing and will be provided with a modulating anode of about unity gain. Figure 19 shows an outline drawing of the tube, and Fig. 20 is a photograph of a Litton klystron, the L3403, which operates at 1250 MHz, 1.25 MW, and 6% duty. A klystron power supply test stand is under construction in the Mockup Building. The block diagram is as follows:



Summary

During the past year, 100-kW models of the three tube types have been operated at LASL, and all appear satisfactory and capable of being scaled to 1.25 MW. Triodes have been tested at 1.25 MW and are satisfactory except that lifetime must be improved. Industry is currently building 1.25 MW versions of all the types, and the several vendors are competing vigorously to produce the best tube.

We estimate installation costs of the klystron and the Amplitron to be comparable, and of the triode more expensive. Power bills for operation would be least for the Amplitron. In the last analysis, however, our experience with the general performance of the three, will determine the systems choice.

Acknowledgment

The portion of this work done at Los Alamos was directed by D. C. Hagerman, T. Boyd, R. Jameson, and T. Turner.

References

1. IEEE, NS-12, 1965, p. 76 et seq.

2. E. Okress, Crossed-Field Microwave Devices, Vols. 1 and 2, Academic Press, New York 1961.

DISCUSSION

D. E. NAGLE, LASL

SMITH, LRL: I'm interested in this question of the life of the triode. What sort of life are you getting, and what is the mode of failure?

NAGLE: Nobody ever determines proper lifetimes at the beginning. In the beginning, one may test one or two to destruction but then, because of budget problems, become more cautious. Several of the earlier versions - when we went to 6% - failed in a matter of a day or so. Therefore, at the moment, we have only one coaxitron, and we're conservative--we run it at 3% for testing components and waveguide tanks.

SMITH: Are they really just not big enough to handle the higher duty factor?

NAGLE: No, they failed for - what seemed to be in many cases - trivial reasons, the kind that should be gotten out of the first tube. Things like improper assembly, and spring-ring contacts being misaligned were, in some cases, responsible for failure. In other cases, more attention should have been paid to anode circuit design and to cooling. One thing we have been noticing in the last few days is that the match between the output coupler and the waveguide is very far from optimum, so the plate is having to take much more of a beating than it should. Possibly, if RCA redesigns this, we might get more efficiency, approaching 55%, which is what we see when we make a model calculation of the efficiency of the tube using basically the structure parameters we have and putting in the electron bunches that go across. This program was put together by Hagerman's group and Hoyt's group and indicates that you should get over 50% in an ideal coaxitron.

SHEEHAN, BNL: How does the collector voltage on the klystron differ from the other tubes; and how does this affect the modulator problem?

NAGLE: How does it differ from the others? The design is for -75 kV on the cathode. The collector is run, of course, close to ground, but we have control of the collector voltage. Don, do you want to say something about this?

HAGERMAN, LASL: I would like to point out that the klystron we have on order has a modulating anode which will be used to turn the tube on and off. In addition, the collector is so arranged that its voltage may be depressed, which means that the capacitor bank regulation requirements are considerably eased. We do not anticipate doing amplitude control of the tube by varying the mod-anode voltage; rather, we will vary the drive.

MILLER, SLAC: Are there any recent developments on depressed cathode, i.e. depressed collector klystrons to raise the efficiency? I mean depressing it by a large fraction of the cathode voltage?

NAGLE: I think it's only for control purposes that we would depress ours. I got the impression from the vendors that it was developmental to improve efficiency this way.

FEATHERSTONE, Univ. of Minnesota: Perhaps this question should be left for the talk that Jameson will give later, but let me at least raise it here. Will you care to compare the three tubes in terms of the stability of drive and stability of supply voltages that they require in order to maintain adequate phase stability?

NAGLE: That the klystron may phase shift with drive is an important consideration, because the drive will be varied to maintain the output parallel. In the case of the triode, the amplitude level is maintained by varying the supply voltage to the anode. There we're interested in the phase shift across the tube with respect to that voltage in order that there not be a strong cross-coupling term between the amplitude portion of the control circuit and the phase shift control circuits. So it's different for each tube, and I think I'll let Jameson comment on the individual characteristics. The over-all statement that he seems to be making is that any one of the three is tractable.

LEISS, NBS: With this difference of drive, the efficiencies that you have shown are maximum saturated efficiencies, I presume, so that with the difference of mechanism of control in rf output, this would seem to work against the klystron considerably on the efficiency point. That is, you have to run off the peak efficiency in order to gain control if you use drive control. Is that correct?

NAGLE: Let me try to rephrase your question to see if I understand it. You say, that in case of the klystron, the efficiency quoted is for optimum drive, so that, if you're going to change the drive by 30%, then the efficiency should drop. Is that your question? I don't believe that's the case for these klystrons. I don't believe that the efficiency in practice will drop substantially.

LEISS: Well, if you hold the klystron voltage and current constant and you get less output, how can it fail to be true?

HAGERMAN: May I interrupt again. I think what Jim said is correct, and what I think we will have to do in practice is that on those days when we want to run with 700-kW output from each klystron (corresponding to no beam loading), we're going to have to drop the cathode voltage. In that way, we will pick up somewhat more efficiency.

LEISS: I was thinking in terms of the power you have to save for making up for beam loading; but really my question was: Does this give preference of one tube over the other of the two types? Since you're going to plate-control the other, the plate will control the other two; and, presumably, the efficiency might be maintained better.

NAGLE: Well, there again, eventually you have a similar problem, in that, you'll also want to reset the plate voltage of the triode so as not to have a long-term condition to where the anode drop across the series switch tube is too high.

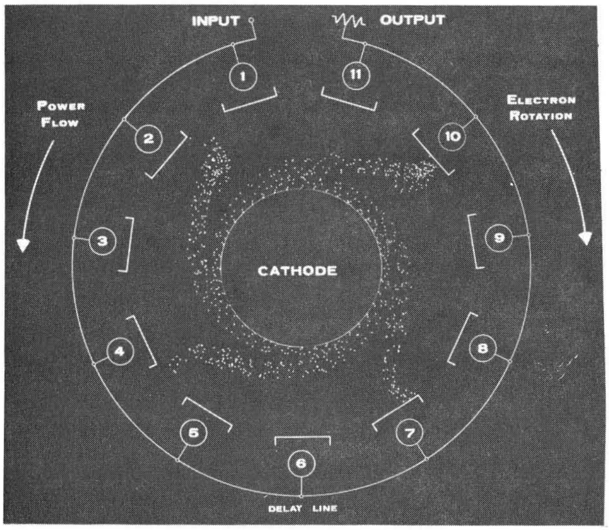


Fig. 1. Amplitron circuit, showing space charge.

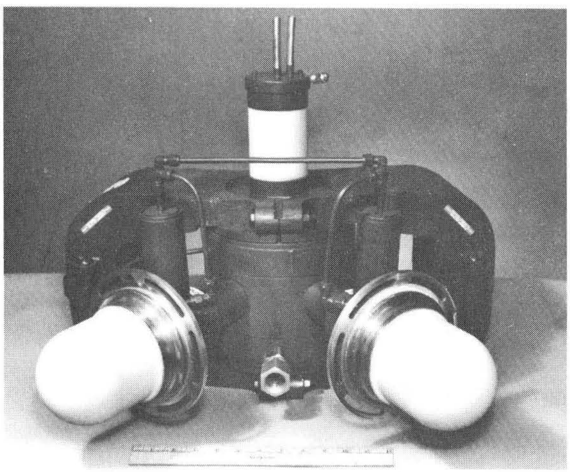


Fig. 3. 100-kW Amplitron, the QKS 1461.

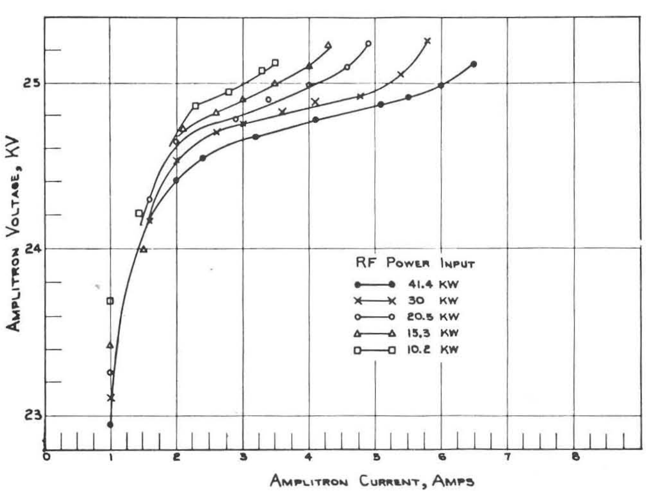


Fig. 5. Anode characteristics for QKS 1461.

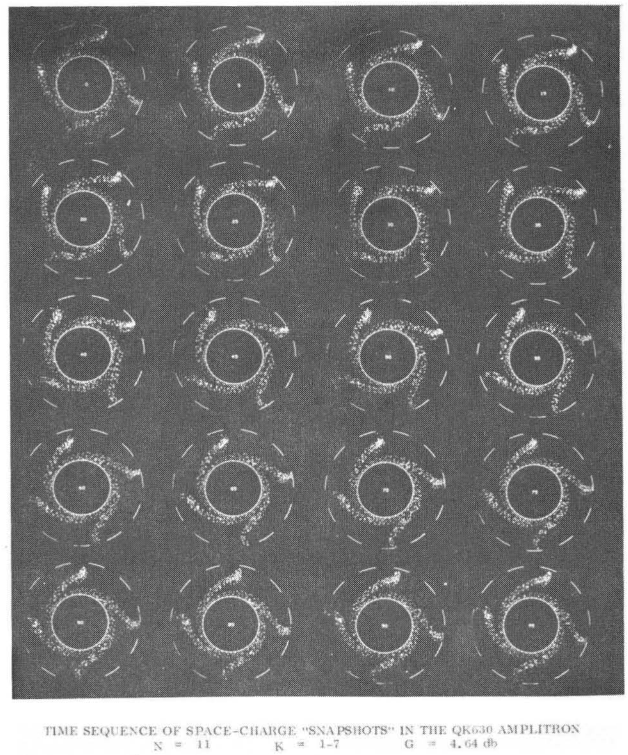


Fig. 2. Computer plot of electron motions.

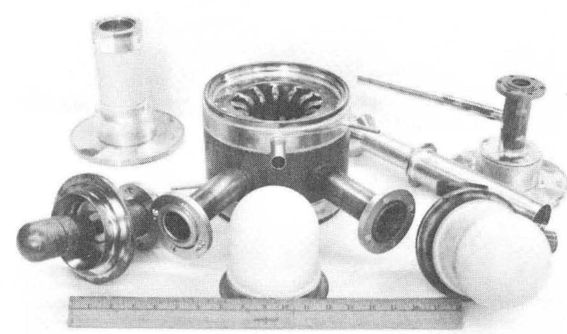


Fig. 4. Parts for Amplitron assembly.

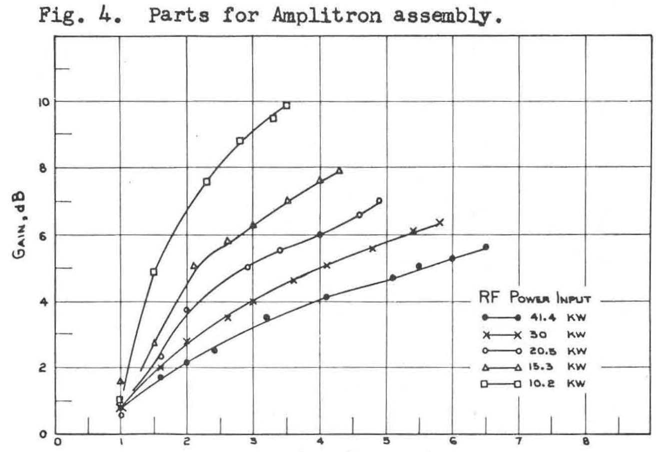


Fig. 6. Gain vs power input and current, QKS 1461.

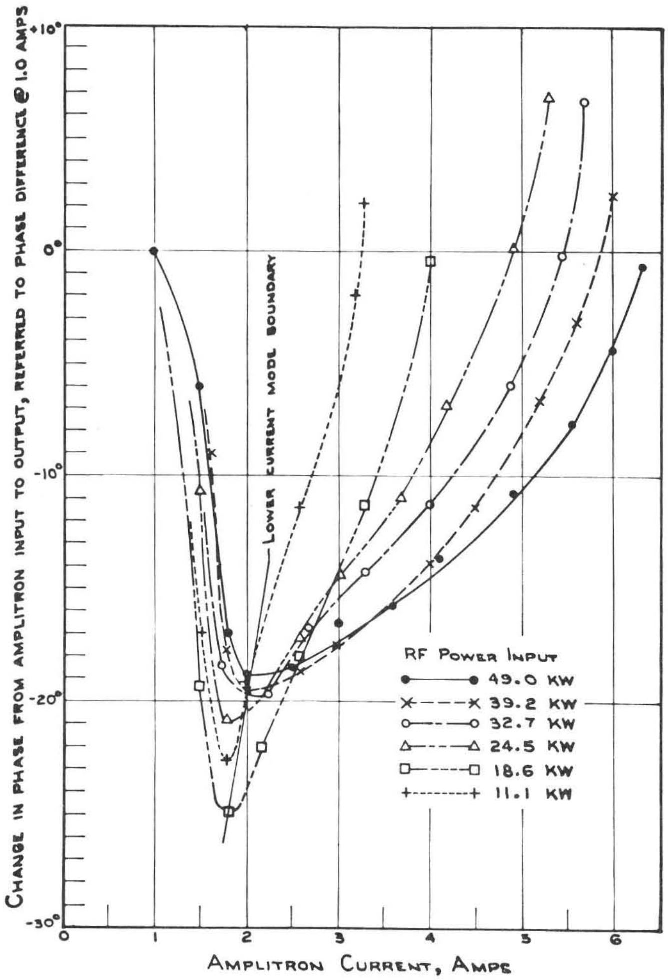


Fig. 7. Phase shift vs Amplitron current and drive.

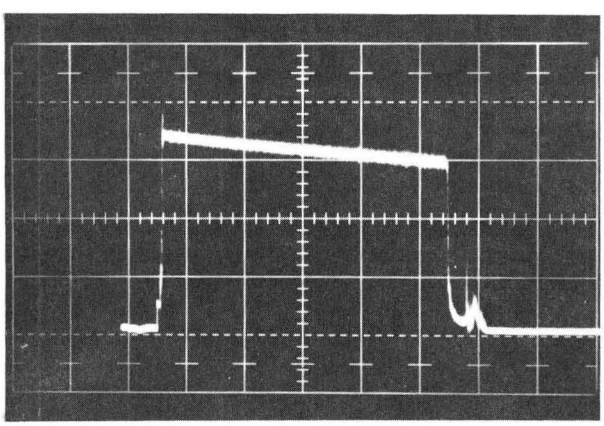


Fig. 8. Output pulse of Amplitron operating near the middle of its range; RF power input 22 kW; vertical scale, 1 A/cm; horizontal scale, 50 μsec/cm. Droop in pulse is a result of condenser bank droop.

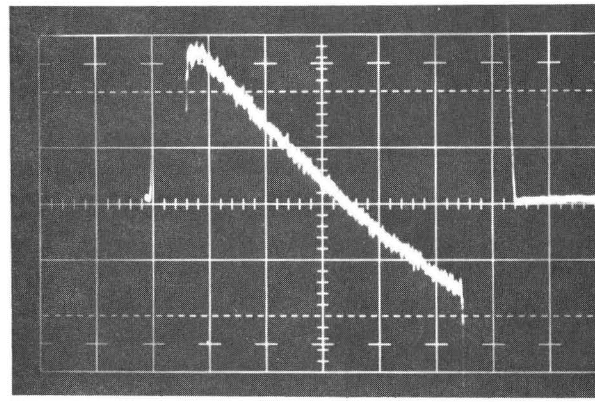


Fig. 9. Phase difference between rf waves into and out of Amplitron at current level and conditions of Fig. 8. Vertical scale 1°/cm, horizontal scale 50 μsec/cm. Change in phase shift is result of condenser bank droop.

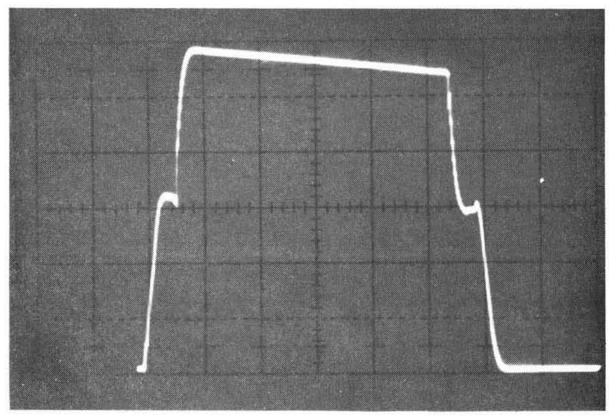


Fig. 10. Amplitude of rf field in 40-cell cloverleaf accelerator section (model B) with approximately 40-kW rf drive to Amplitron and Amplitron current near upper mode boundary. The klystron pulse overlaps the Amplitron pulse at beginning and end, and is fed through to output.

Fig. 11. Coaxitron parts.

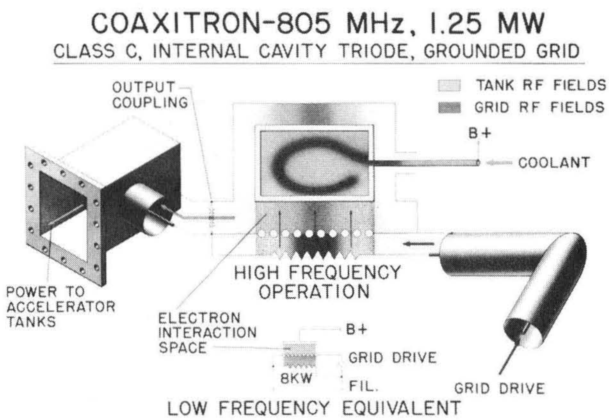


Fig. 12. Operating schematic of coaxitron.

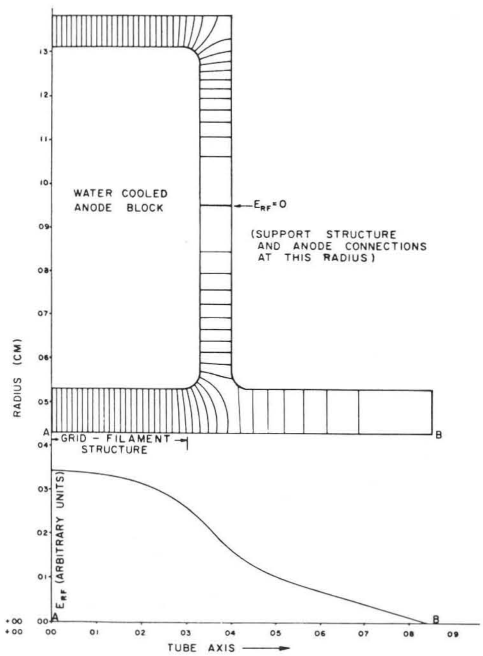


Fig. 13. Internal field plot of coaxitron.

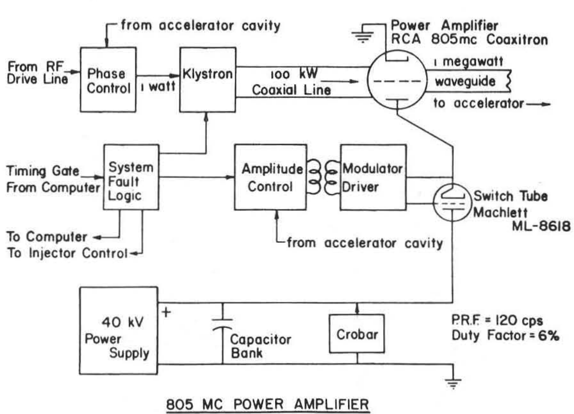


Fig. 14. Arrangement for coaxitron test.

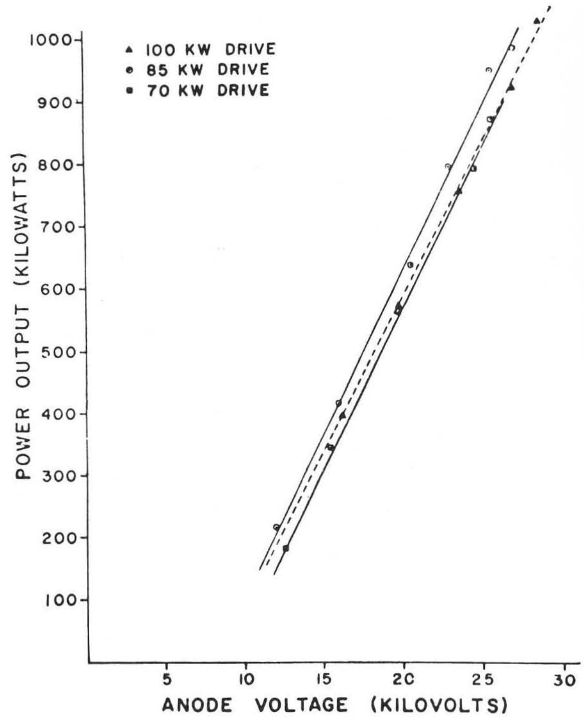


Fig. 15. Coaxitron output vs anode voltage and drive.

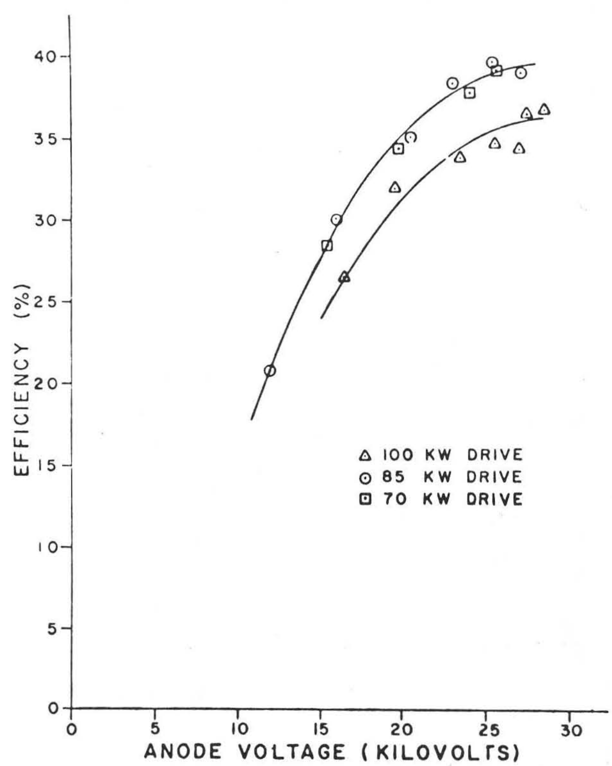


Fig. 16. Coaxitron efficiency vs anode voltage and drive.

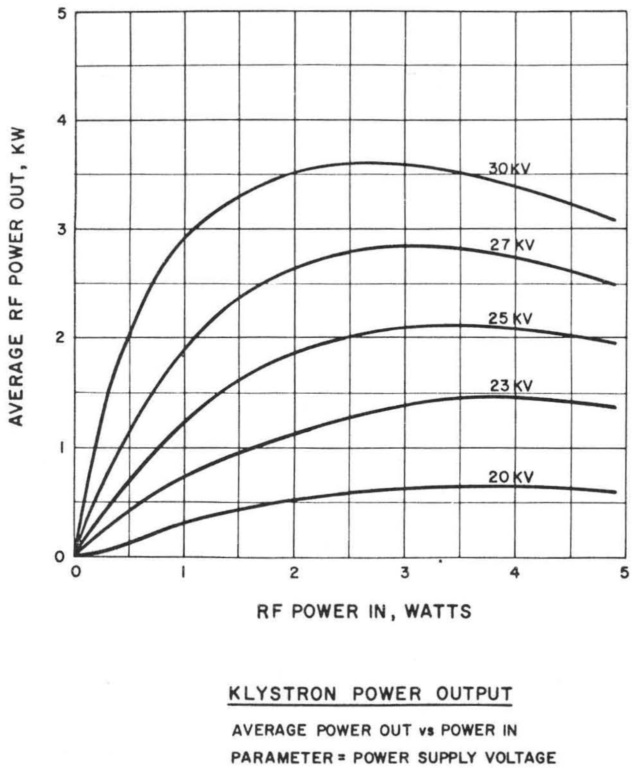


Fig. 17. Output power vs drive and beam voltage (Eimac).

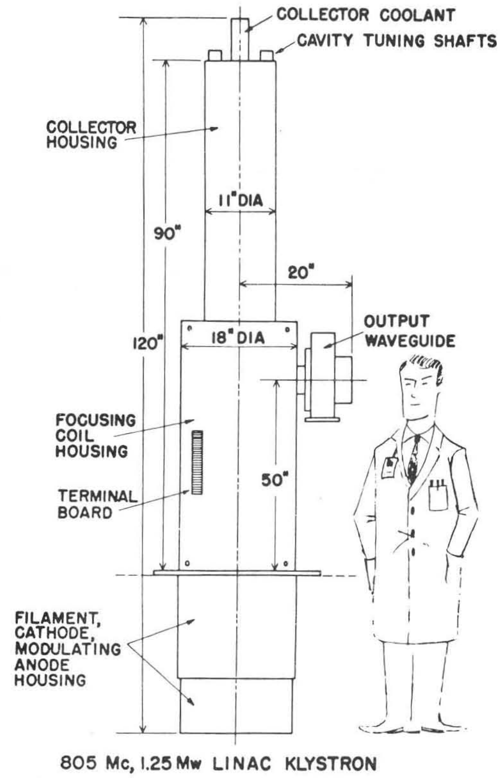


Fig. 19. 1.25 MW klystron outline drawing.

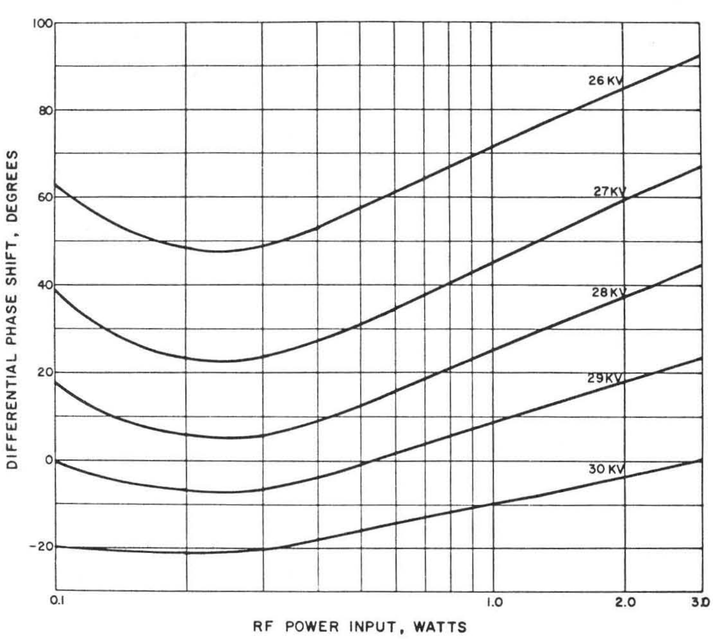


Fig. 18. Phase shift vs drive and beam voltage (Eimac).

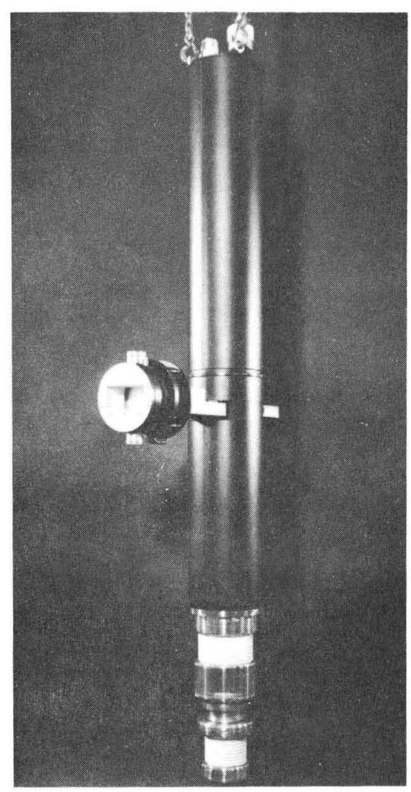


Fig. 20. Litton klystron, peak power 1.25 MW, duty 6%, frequency 1250 MHz.