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RF SOURCES DEVELOPMENTS*

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Abstract

The continuing need for accelerators of increasingly sophisticated characteristics requires a great variety of rf sources to provide the energy used by these accelerators. The present status of gridded tubes will be reviewed briefly. Klystrons, which are used in most large accelerators, will be considered in some detail. Their limitations in power and frequency will be reviewed and a study of their reliability will be presented. Improvements in their efficiency will be discussed, and trends for the future will be considered. Some limitations caused by material problems will become evident and a review of some of the potential improvements in that area will be considered. Finally, new types of rf sources based on rotating electron beams which are now in the development stage will be described and compared to existing tube types.

Introduction

The present status of rf sources for accelerators has been discussed extensively by Tallerico at the San Francisco Particle Accelerator Conference in March of this year,[1] and I refer those interested to that paper. We will simply state that the present power limitation of gridded tubes (triodes and tetrodes), used at frequencies up to 200-250 MHz, is approximately 1/2 MW average at 200 MHz. Gains of 10 to 20 dB are typical. Plate efficiencies up to 90% can be achieved although commercially the overall efficiency is only slightly over 65%. Technological developments, particularly the introduction of pyrolytic graphite grids, show promise to almost double the power available at a given frequency from a single tube in the next few years.

Probably because of a tendency to moding and oscillations when feeding a non-matched load, crossed-field amplifiers have never successfully been used in large linear accelerators in spite of the obvious advantages of high efficiency at frequencies up to 10 GHz. However, magnetrons are used extensively in commercial accelerators.

The remainder of this paper will consider the status of klystrons which are most widely used in high power accelerators. We will review the SLAC experience with klystron reliability, and discuss the physical basis for electron tube efficiency, pointing out why klystron efficiency has been generally lower than that of other tube types, and what is being done to improve it. Finally, we will look at a promising development in field emission cathodes,[2] and at the possible advantages of new tube types such as gyrocons[3] and trirotrons[4] which operate on the principle of beam deflection modulation.

Klystron Reliability and Operating Cost Considerations

The bottom line on feasibility of new accelerator development or total operating time of existing machines depends to a great extent on the cost per operating hour of the rf sources. This cost consists of three main components: capital or replacement costs, energy cost, and maintenance costs. Hourly replacement costs can be expressed as individual source initial cost divided by Mean Time Between Failures. Energy cost is the cost per kW hr. at the mains divided by rf system efficiency. Klystron MTBF observed at SLAC should be a good indicator of attainable reliability.

Good statistics have been gathered since 1965 from a line of approximately 250 pulsed klystrons operating at 2856 MHz. Their power output has been gradually upgraded from 21 to 40 MW peak and from 20 to 40 kW average. Since the beginning of operations, SLAC has operated a total of slightly more than 1,000 tubes, and the operating hours have reached nearly 16,000,000. For energy conservation reasons the repetition rate of the tubes which was mostly 360 pps during the first years of operation has now been dropped to 180 pps or less for the majority of the runs. Hence, the statistics available on tube life may be skewed by the changes in operating conditions. One would expect an increase in life due to the reduced repetition rate; on the other hand, one would expect a decrease in life due to the gradual increase in both peak and average power of the tubes on the line, since part of the increase was achieved by increasing operating voltage. With these caveats, I am presenting in Fig. 1 three curves showing the overall tube life expectancy, including the Mean Time Between Failure

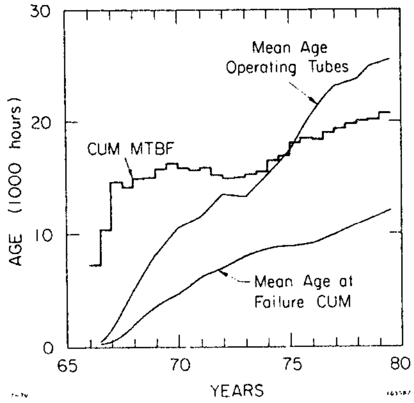

Fig. 1. Klystron operating experience at SLAC.

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since initial operation, mean age at failure, and mean operating age of all tubes on the line. It is worth mentioning at this time that 18 tubes (over 7% of the total complement) have operated for 60,000 hours or more without noticeable degradation in performance. Figure 2 gives the age distribution of all operating and failed tubes since the beginning of operation and Fig. 3 gives the failure probability for all tubes and for SLAC - built tubes.

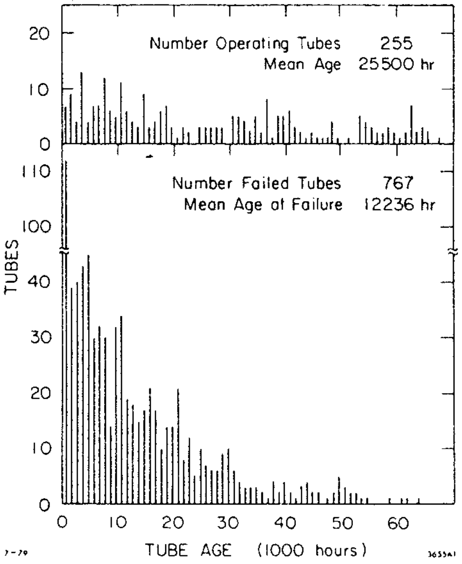


Fig. 2. Klystron age distribution at SLAC (9/1/79).

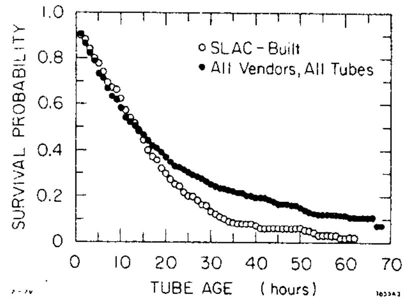


Fig. 3. Klystron survival probability.

The failures must also be analyzed be causes, if one hopes to gradually improve the tube reliability. Results of this analysis are shown in the table below, which gives the percentage of tubes failed by the major causes since the beginning of operation.

As can be seen from the table, the overall percentage of failures is approximately 25% for emission problems, 25% for cathode anode arcing problems, 25% for output window problems; 1/6 of all failures were caused by loss of vacuum, 5% by instabilities in the rf output, and only 2% by H. V. Seal failure. In addition, a few tubes were damaged mechanically by mishandling, and they are not counted in the table.

Percentage of Failures by Causes

Vendor	Vacuum	Emiss.	Arcing	Window	Output	H.V.Seal
A	13	9	19	51	5	3
B	49	6	21	16	8	0
C	18	34	26	17	4	1
D	7	38	32	13	6	4
All	16	26	26	25	5	2

Although the overall failure distribution is reasonably uniform, it is interesting to note that 50% of the failures of one of the vendor's tubes were caused by window failures, whereas another vendor had 50% vacuum failures.

Obviously, no conclusions can be drawn from the table without knowing the age of failure by the different mechanisms, but the indications are that the existing technology is not uniformly known or applied by the various vendors, otherwise there should not be this great discrepancy in the percentage of failures caused by different mechanisms.

Other types of klystrons are also used at SLAC, which has lately built all the tubes needed for its operation. The total usage to date of these types does not warrant definitive statements about their reliability. However, the 125 kW cw 353 MHz tubes used at SPEAR have now accumulated 80,000 hours of operation in 4 sockets, and the indications are that their MTBF will be as high as that of our pulsed tubes. We are also installing at PEP a dozen tubes designed to operate at 353 MHz and to produce 500 kW of cw rf. We believe that the life of these tubes will be similar to that of our pulsed tubes, and will use that assumption to demonstrate the effect of MTBF on rf hourly costs.

As an example of the total tube cost per hour, let us consider the PEP 500 kW cw klystrons, which cost about $100,000, or $200/kW rf out. Assuming 20,000 hours MTBF, the capital cost per rf kW hour is 1¢. At SLAC, the cost per kW hour is about 0.5¢. With a tube efficiency of 63%, the energy cost per rf kW hour is thus about 0.8¢. Increasing the tube efficiency to 70% reduces the power cost to 0.7¢. It is interesting to note that, for the above assumptions, a 10% increase in MTBF will reduce the overall cost per hour as much as a 10% increase in efficiency.

Efficiency Considerations

The electronic efficiency of a microwave amplifier can be defined as the ratio of the power extracted from the beam in the output system to the beam power. To maximize efficiency, as much energy as possible must be extracted from every electron in the bunch. If a bunch of electrons in the beam enter the output with exactly the same velocity and the same rf phase, then the energy extracted from that bunch will be the same for all its electrons, except for space charge effects. In principle, 100% efficiency can be obtained if all electrons are exactly stopped as they pass through the rf output system.

The work towards improving klystron efficiency has thus been directed at first decreasing the bunch size so that as many electrons as possible will be decelerated by the same potential. The addition of second harmonic cavities and changes in the accelerating structure length have been used to minimize the velocity differences of the electrons as they enter the output gap.

An overall view of the present status of klystron efficiency is given in Fig. 4.

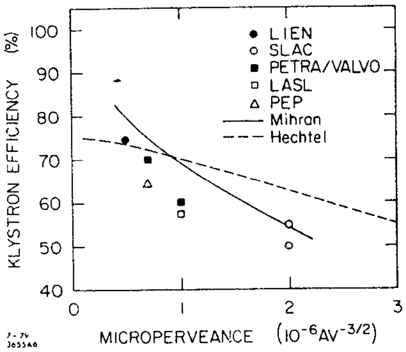


Fig. 4. Klystron efficiency vs. perveance.

The two curves labeled Mihran[5] and Hechtel[6] were obtained by analysis of the references given. Mihran's work has dealt mostly with computer simulation of the beam bunching by disc models, whereas Hechtel considered mostly the effect of the potential depression in a solid beam. The points shown represent measured data from actual tubes. For SLAC we give the best efficiency achieved under special test conditions as well as the best normal efficiency. LASL represents the operating efficiency of the Varian klystrons used on the LAMPF linear accelerator. The PEP efficiency is that obtained for the PEP storage ring klystrons. Lien[7] gives the results of a tube built at Varian Associates to confirm theoretical predictions made by Lien on the effect of second harmonic cavities, and finally the two points PETRA/VALVO show the normal operating point of a VALVO built klystron in the PETRA ring at microperveance 1, and the best efficiency obtained in special studies of the same tube after decreasing the perveance by modulating anode voltage adjustment and readjusting the focusing conditions and the output load.

The general trend shows a decrease in efficiency with increase in microperveance, which can be understood from general space charge force considerations. The increases in efficiency resulting from the use of second harmonic cavities and careful detuning of penultimate and prepenultimate cavities of multi-cavity klystrons enables the formation of a bunch of optimum size in which all electrons have substantially the same velocity as they enter the output gap.

One of the main reasons why rotating beam tubes such as the gyrocon and the trirotron can have much higher inherent efficiency than klystrons is because in those tubes all electrons in the beam can be made to enter the output resonator at a substantially constant phase with respect to a traveling wave in that resonator, because basically the velocity spread is very much smaller and because the beam area entering the output is much larger than for a klystron of similar frequency range and power resulting in lower space charge problems in the output cavity.

From the above considerations one can deduct that further improvements in klystron efficiency should result from the use of hollow beams to minimize the potential depression. Also, in all tube designs, engineering compromises have to be made. For instance, higher cathode current density might result in a higher efficiency, but the life expectancy could be seriously reduced. Similarly, higher beam current density might increase the magnetic field requirements. In most cases, the final choices are dictated by the availability of materials, and new or better materials and techniques could well result in higher efficiency without reducing the probable tube life.

Further Klystron Work

Although SLAC has no specific plans for new klystron types at this time, it is always useful to speculate on the next improvements of existing tubes, or on the next generation. At the present time, the improvements to the pulsed tubes consist mostly of material studies, particularly in the cathode region. Based on experience to date, there is a potential improvement in MTBF by a factor of 2 approximately, by simple preventing failures by temperature limited cathodes. Unfortunately, this is a very slow, tedious engineering work requiring extreme patience, since the result of today's changes will not be known for approximately 4 years.

On the other hand, the PEP cw tubes have never yet demonstrated the efficiencies which had been predicted by our computer results. Here, work is proceeding on parallel approaches - one, a further study of the assumptions used in the computer code and their modifications; second, an experimental approach where the present PEP gun will be replaced by a hollow beam gun. The improvement in beam coupling coefficient and the fact that all the electrons in the hollow beam are decelerated by a more uniform field in the output gap than those of a solid beam lead us to expect a substantial efficiency improvement.

For the future, SLAC is looking at klystrons with two completely different applications. One, to be used in very high energy storage rings, would operate in the 500 to 1000 MHz region, with peak and average powers up to 20 MW and 1 MW respectively at 500 MHz; and one half that at 1000 MHz. In order to conserve power, the tubes would be designed to operate pulsed, with a pulse length of approximately one microsecond, and a repetition rate of between 20 and 60 KHz. The main development needed to make such tubes practical is a gridded gun with a low cut off voltage. Some useful development work is being done at Varian. We believe that a hollow beam gun could be another approach resulting in a satisfactory design; and finally, that the field emission gun to be discussed later may have all the desirable characteristics.

We are also looking at the feasibility of pulsed klystrons operating @ 2856 MHz, with peak and average powers of approximately 100 MW and 50 kW respectively. Some thought has been given to the design optimization, looking first at the choice of perveance. Taking a conservative average through the data of Fig. 4, one can draw a single efficiency curve as on Fig. 5.

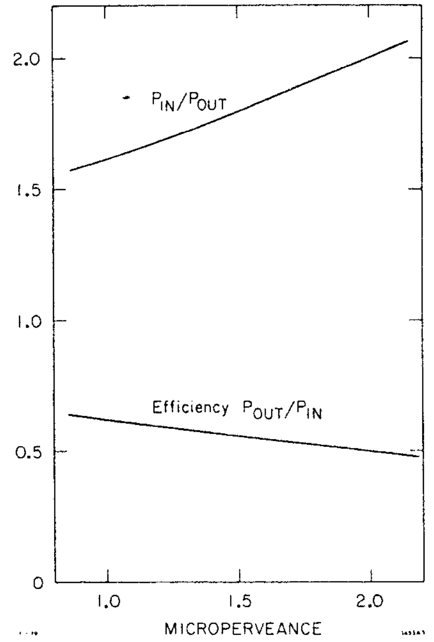


Fig. 5. Effect of efficiency on line power requirements.

The reciprocal of efficiency is also plotted, and shows the savings to be achieved in electrical capacity by decreasing perveance. Figure 6 then computes the beam voltages and beam currents needed to achieve a given power output at a given perveance. The final choice, which has not been made yet, will be determined by the best compromise between magnetic field requirements, breakdown voltages, and cathode loading.

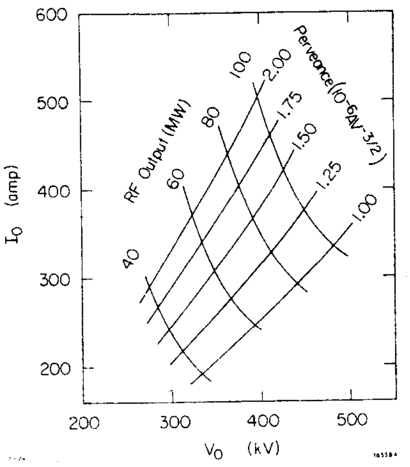


Fig. 6. Voltage-current design characteristics of high peak power klystrons.

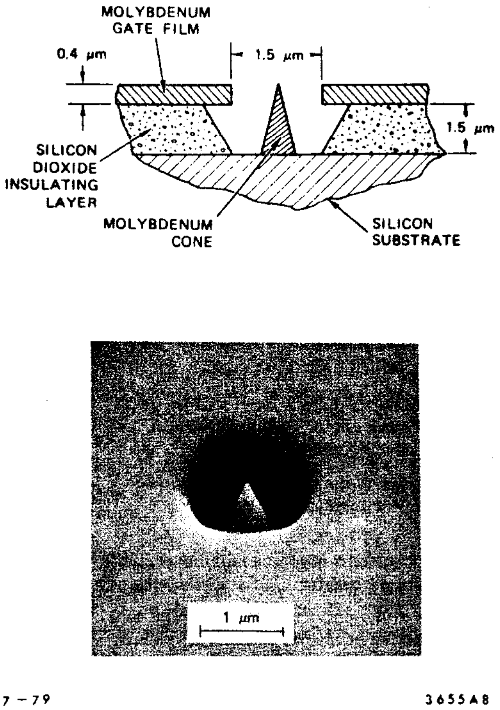


Fig. 7. Schematic diagram and scanning electron micrograph of thin-film field emission cathode (TFFEC).

New Cathodes

A technical advance which has been waiting many years but seems to be on the verge of successful application to electron tubes is that of field emission cathodes. Work has been carried out at SRI International for many years to develop field emission cathodes which are fabricated using thin film technology and microlithography.[2,8] Called thin film field emission cathodes (or SPINDT cathodes), they consist of a series of micro cones as illustrated in Fig. 7. These cones are capable of cw emissions of between 20 and 25 microamps each and they have been stacked in densities of up to 22,000 per square millimeter. The evidence indicates that the emission is stable with time, is a function of the residual pressure but regains its initial value after the vacuum is re-established to its original operating level (Fig. 8), and that even after 38,000 hours of operation at a level of

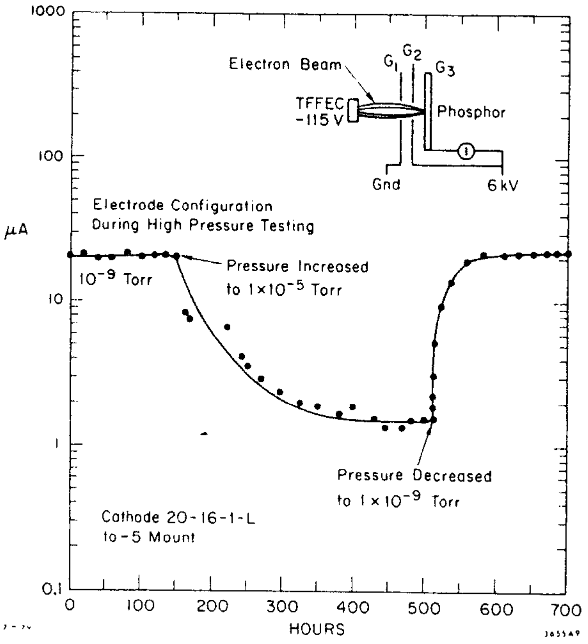
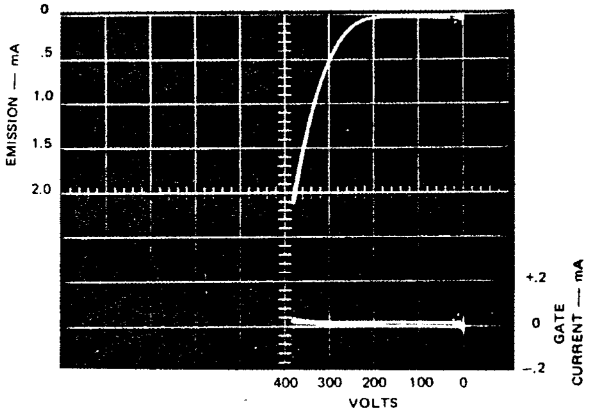
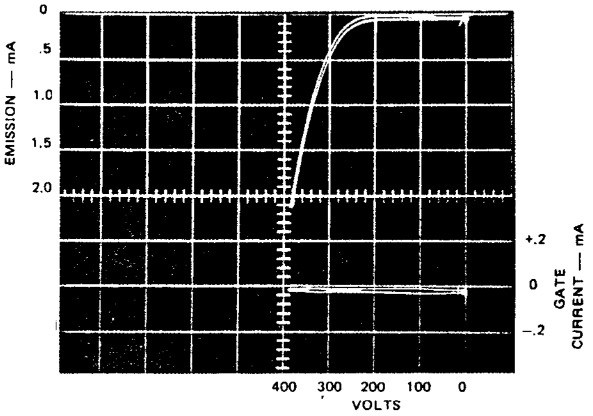


Fig. 8. Effect of ambient pressure on emission.



(a) START OF LIFE TEST (MARCH 7, 1975)



(b) EMISSION AFTER 33,000 HOURS (DECEMBER 11, 1978)

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Fig. 9. Current-voltage oscillographs for 100-cone array driven by a 60-Hz half-wave voltage to a peak current of 2-mA for 33,000 hours.

20 microamps per cone, the characteristics of these thin film field emission cathodes do not alter appreciably (Fig. 9).

If these cathodes can really be proven to be a reliable source of electrons for high powered vacuum tubes one must rethink the basic design of many tubes. For instance, the PEP tube is now operating at a beam voltage of 63 kV and a current of about 12 amps; with a standard oxide cathode of approximately 12 cm diameter, the cathode current density is approximately 100 ma/cm^2. Using a SPINDT cathode, at a current density of 12 amps/cm^2 an emitting area of only one cm^2 is needed. This in turn means that one could consider an annular cathode of approximately 5 cm outer diameter and 4.9 cm inner diameter, producing a beam of equal dimensions. Controlling such a beam may impose difficult magnetic field requirements, but also means that all electrons reach the gaps at the same value of electric field and should result in a substantial efficiency improvement. Similarly, a high power pulsed cathode could be operated at current densities well in excess of 100 amps/sq cm which in principle would allow us to reduce the beam and drift tube diameters or to use annular beams. Finally, these cathodes should be of great value in the design of easily controllable beam current tubes, since a control potential swing of less than 200 volts results in a current swing of at least 5 orders of mangitude (Fig. 10).

Deflection Modulation or Rotating Beam Tubes

Work on different types of electron tubes has lately shown promise of successful development. Although the original concept was first proposed in 1946 by J. W. McRae,[9] and suggested again in 1966 by Preist,[10] it is not until Budker[11] demonstrated efficiencies of better than 75% on pulsed gyrocons at Novosibirsk that work began in this country on the study and further development of these devices.

Basically, the deflection modulation or rotating beam tubes are capable of extremely high efficiency because of the special output circuit design. The output circuit is a resonant waveguide ring sustaining a traveling wave. The beam is made to rotate at the resonant frequency of the ring. Hence, an electron beam without any velocity modulation can be made to enter the output resonator at always the same phase with respect to the traveling wave. Referring back to the efficiency considerations, we have here what is probably an ideal solution, since the beam always sees the exact same fields in the output circuit, and all electrons enter with the same velocity except for the variations caused by space charge.

The gyrocon, which is being studied at Los Alamos by Tallerico,[12] depends on deflection modulation of a cylindrical beam to produce the rotating beam. Figure 11 shows the basic concept of the gyrocon deflection and focusing. A solid beam,

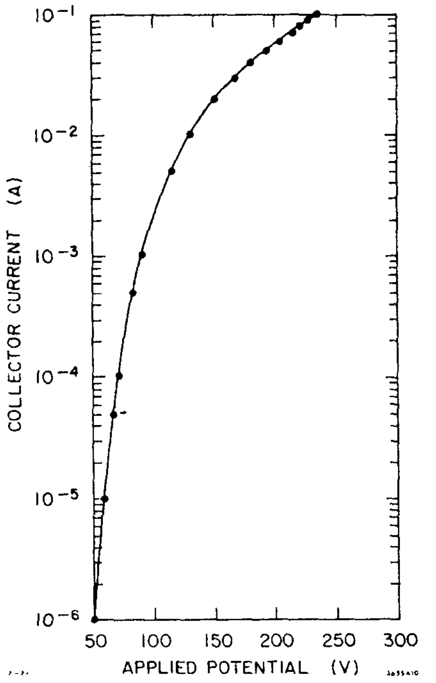

Fig. 10. Collector current vs. cathode voltage (5000 cone array).

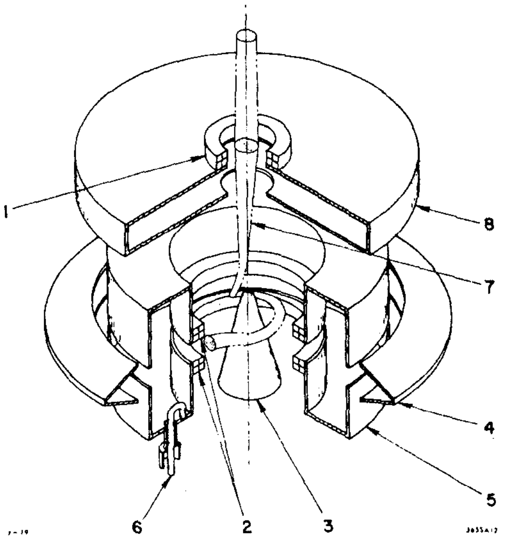

Fig. 11. The radial gyrocon: (1) gun focus coil, (2) output focal coils, (3) bender, (4) collector, (5) output cavity, (6) rf output, (7) electron beam, and (8) deflection cavity.

starting at the top of the figure from a standard electron gun, is focused by gun focus coil. The deflection cavity can support two space-orthogonal modes at the same frequency. If the two modes are fed 90° apart in phase, a rotating electric field normal to the axis of the cavity results. This field deflects the beam by a constant angle, generating a cone. The beam then enters the DC magnetic field of the bender magnet, increasing the deflection angle until the beam direction is normal to the axis. At that point, the beam is refocused in the vertical plane by coils before entering the output waveguide cavity. The spent beam energy is dissipated in the collector, and the power extracted from the beam in the output resonator is transferred to the load by two or more couplers, usually orthogonal in space.

A computer code has been developed to follow the beam through the complete deflection and output system of a gyrocon being built at Los Alamos. The computer model, which includes space charge effects, indicates an electronic efficiency in excess of 90% and an overall efficiency of about 85%. The tube is designed to operate at 450 MHz. With a modulating anode gun operating at 86 kV and 9 amps, the power output should be in excess of 650 kW with a gain of approximately 20 dB. As can be gathered from the description above, the overall drive-deflection system of the gyrocon is extremely critical. Any asymmetry in the drive cavity will result in an elliptical cone, since the deflection angle will be different for different rf phases. Hence, the beam will no longer be deflected uniformly by the DC magnetic field. Also, any variations in beam voltage or deflection magnet current will result in improper deflection. The result is need for very careful monitoring and feedback. With the use of micro-computers, it should be possible to solve these problems.

Planar type gyrocons in which electrons travel radially from an rf driven cathode, through an accelerating gap and into the output resonator could alleviate some of these problems. The trirotron[4] work being done at SLAC is an attempt to develop a possible solution. The trirotron's drive system is a circulating waveguide resonant at the drive frequency, and is concentric to the output resonator. By adjustment of the phase propagation constant of the two resonant waveguide rings, the input resonator guide has a smaller diameter than the output, allowing for the application of DC accelerating field between them. The cathode, insulated from the remainder of the waveguide, replaces the central portion of the inner wall (Fig. 12) and is opposite a series of grids on the outer wall to allow the electron beam formed in the drive resonator to reach the DC accelerating fields.

By adjusting the relative values of E_0 and E_{bias}, it is possible to control the beam spread from 0 to 180° and to vary the total emission, although not necessarily independently. Some of the current emitted from the cathode never exits the input waveguide because of the reversal of the rf field during the transit time. Those electrons are then returned to the cathode, and absorb more than half of the total rf power supplied to the

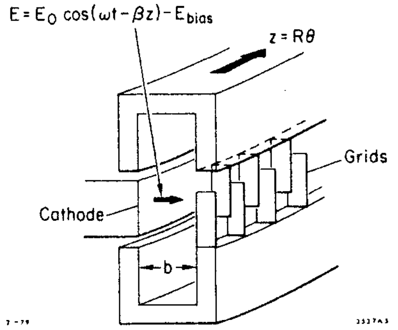

Fig. 12. The input resonator: beam formation region.

input circuit. Better choices of rf fields, DC bias, and waveguide height "b" should improve the situation, and the optimization process will continue before final design.

The production of a pure traveling wave in the input circuit is essential if good performance is to be achieved. Since a backward wave can result from relatively small reflections in the traveling wave resonator and input couplers, great care should be taken to locate two identical input coupling loops exactly 90° apart, each fed by the same power phased TC/2 apart. Also, two sets of tuners will be required to match out any residual reflections in the input circuit.

The output efficiency has been analyzed using a modified version of the computer program developed by Tallerico for the gyrocon. The results are shown in Fig. 13 for a beam assumed to extend approximately ±9% from center of the axial output resonator length. Indicated efficiencies of 85% at 1 radian beam spread and 80% at 1.5 radians are very encouraging. It appears reasonably easy to produce a 1.5 radian beam; at 1 radian, the total current available might be too low to be of value for very high power tubes. An improvement of a few efficiency points can be made by adding a very small axial magnetic field, which counteracts the beam deflection caused by the rf magnetic field.

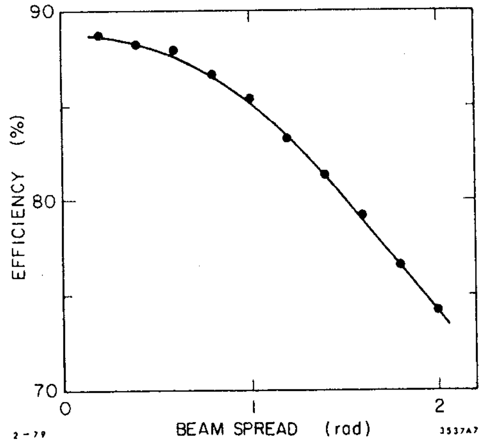

Fig. 13. Output efficiency vs. beam spread angle.

The results of the studies carried out has led us to design a trirotron to operate at 353.2 MHz, at beam voltages of 56 to 64 kV and currents of 8 to 12 amps. The conceptual drawing is shown in Fig. 14. The following dimensions have been used:

Cathode diameter	27.65 cm
Axial cathode length	9.00 cm
Input resonator OD	29.65 cm
Input grid fins	1 × 9 × .07 cm
Output resonator ID	37.65 cm
Output resonator OD	57.65 cm
Axial output resonator length	51.50 cm
Collector OD	80.00 cm
Axial Collector length	20.00 cm

Efficiencies listed in the following table were computed assuming a uniform density beam, spread over 80° (produced by a drive power of ≃ 10 kW), with an axial length of 10 cm and no magnetic field efficiency enhancement.

	KV	56	60	64
Amps				
8		81.1	80.4	81.0
10		81.4	81.4	81.3
12		80.7	81.6	81.4

The trirotron shows promise of being a highly efficient device at frequencies of 200 to 500 MHz, and power outputs of one-half to several MW cw. The efficiency is not a critical function of beam voltage, drive power, or bias voltage. Hence it appears possible to control the power output over a wide range by adjusting the DC bias or the drive power without loss of efficiency and with minimal phase variation between input and output. Some possible disadvantages include the drive system DC isolation, the need for accurate tuning of the input resonator and its coupler, the cathode heating by electron back-bombardment, and the low gain computed at approximately 15-18 dB.

Conclusions

At frequencies of 200 MHz or less, the gridded tubes will apparently remain the dominant type; and one should expect to see their power capabilities double during the next few years. At frequencies of between 300 and 1000 MHz, there should be within a few years a choice between klystrons and rotating beam devices. The maximum obtainable power output should be the same for both devices, since it will almost certainly be determined by output window design considerations. One can expect 20 MW peak and 1 MW average at 500 MHz, varying in inverse ratio to the frequency. It is also likely that this limit could be increased by additional window development.

The rotating beam tubes will probably have efficiencies of 80 to 85%, with gains of 15 to 25 dB. The possibility of rf leakage from the

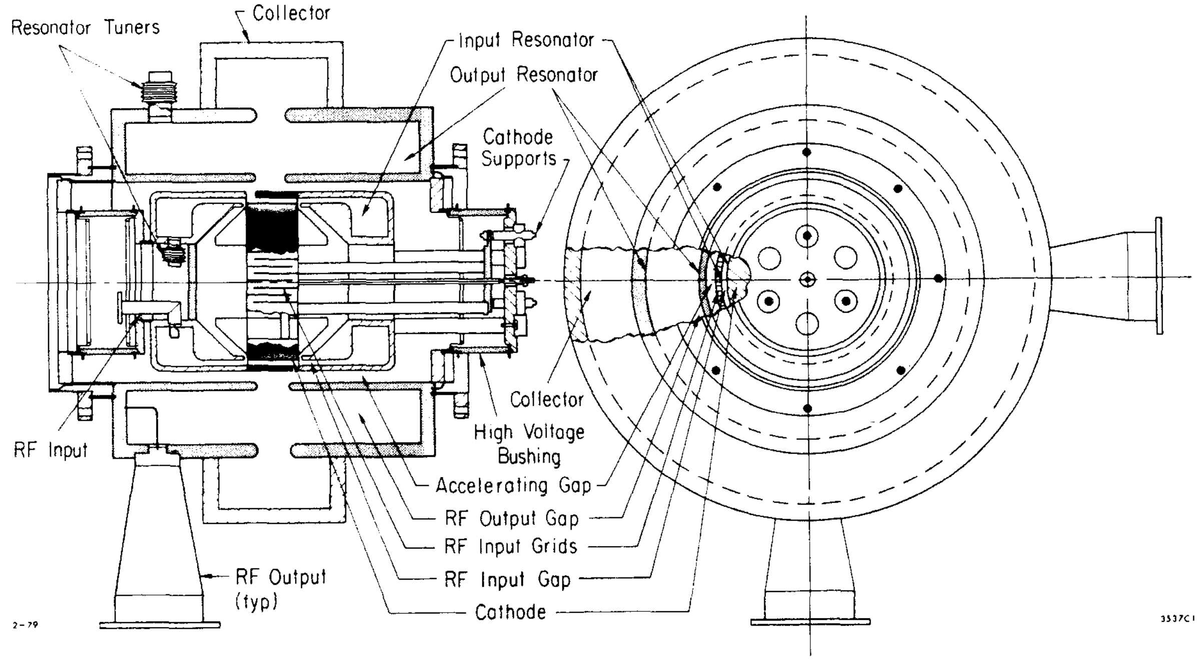

Fig. 14. Conceptual design of a 600 kW, 353 MHz trirotron.

output resonator through the beam entrance slot may produce unknown challenges and unpredictable oscillations. Finally, nothing is known about their probable life of operation, since the only experience at Novosibirsk has not been too favorable. The klystron efficiency in that frequency range is now between 65 and 70%, and computer studies indicate that the next generation will show efficiencies around 75%, with a gain of between 40 and 50 dB. The choice between the two candidates will revolve around the merits of the slightly better efficiency of one compared to overall system simplicity and reliability of the other.

From 1 to 10 GHz, the klystron is still probably the only candidate for large machines. Peak powers of 100 MW should not be difficult to attain at low repetition rates and short pulses, keeping the average power to 50 kW, at frequencies around 3 GHz. The tube life is excellent and the efficiency should gradually increase to about 55 to 60% with good gain.

Above 10 GHz new tube developments are taking place, but they have not been dealt with in this paper, since they are probably of limited interest to this audience.

Acknowledgements

The author wishes to thank the various people in the tube industry who have given of their time while he was researching the status of tube types not in his own immediate field. He wishes to express particular appreciation to Tallerico and Spindt who have kindly agreed to let him use in this paper some of the figures they had published elsewhere. He is grateful for the help he received from his co-workers at SLAC, and particularly to Alice Kalthoff who did the ground work for the klystron failure analysis.

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