COMPUTER DESIGN OF UHF POWER AMPLIFIER TUBES*

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Summary

Improved computational methods have been developed which can reduce the trial and error process in the development of certain microwave power tubes that employ cavities with cylindrical symmetry. It has been found, for example, that the application of these computer codes to klystron cavities and internal cavity triodes reveal ways in which their performance can be improved and results in better understanding of experimental results. The computed results agree quite closely with measurements made of such quantities as frequency and operating efficiency.

Introduction

This paper describes some work done at the Los Alamos Scientific Laboratory on the application of the LALA computer program to microwave power tubes. The LALA program is described by its originators in Reference 1. It was originally developed to aid in the design of linear accelerator cavities and has been very valuable in generating configurations with improved performance. Because of the similarities of these cavities to certain microwave power tubes (or parts of power tubes), the program can also be successfully applied in this area. The basic requirements are that the cavity being studied possess cylindrical symmetry and that it resonate in the lowest frequency mode consistent with the absence of electric field variations in the azimuthal direction. If these criteria are met, the program can be used in preliminary design calculations to predict resonant frequency, field distributions, and efficiency of a wide range of cavity shapes.

Further descriptions of the LALA program are given in References 2 and 3. Fundamentally, it solves Maxwell's equations subject to the appropriate boundary conditions and determines the magnetic field at mesh points which may number typically ten thousand in a given UHF cavity. The actual cavity boundary, which is made up of metallic surfaces and planes of symmetry, is approximated in a zigzag fashion by the mesh lines and difference equations are employed to determine the magnetic field on the actual boundary. To successfully apply the program to a given cavity, it is necessary to know approximately what the true magnetic field and frequency are as a starting point. If no such approximation is available, it is necessary to start with a cylindrical cavity for which the solution can be found analytically and then to arrive at the final configuration through a series of small changes in dimensions.

Because of the versatility of such a mesh program, its range of applications to microwave power tubes is large; two will be discussed here. The first application is a resonant cavity of the type used in klystrons for bunching the electron beam. Here the problem is almost identical to the linac cavity and the designer commonly wishes to know resonant frequency, field intensities which locate potential sparking points, Q of the cavity and some measure of performance such as the following:

$$ZT^2 \propto (\Delta\epsilon)^2/P \qquad (1)$$

where Z is the shunt impedance per unit length and T is the transit time factor. By maximizing ZT^2, the energy ($\Delta\epsilon$) gained by the accelerated particles per unit power dissipated in the cavity walls (P) is maximized. Neglecting multipactoring, energy wasted in wall currents are the only losses in the cavity. A somewhat different situation exists in the second application to be discussed. In this case, an internal cavity triode (coaxitron) is analyzed in which the major power loss is due to energy contained in the electrons as they pass through the grid-anode space and strike the anode. By comparison, the power loss due to wall currents is insignificant (1-2%). In this application, the electric-field distribution and frequency are desired. By knowing the field, two functions can be served: (1) A calculation can be made of operating efficiency when the tube is driven as a power amplifier, and (2) points of low electric-field intensity can be found at which physical supports for the anode (coolant pipes, etc.) should be located. These pipes will, of course, disturb the cylindrical symmetry of the cavity but in many cases deviations from the computed fields are small and the purposes of preliminary design are still satisfactorily met.

Analysis of a Klystron Buncher Cavity

The overall buncher cavity dimensions were obtained from a 1.25-MW, 805-MHz klystron designed for the 800-MeV Los Alamos proton linear accelerator. The computation was started with an analytic solution of a right circular cylinder having these maximum dimensions as shown in Fig. 1A. The electric-field lines shown have only a radial variation about the axis of revolution and the frequency is 1.339 GHz. In the next step, the cavity length and the drift tube hole are established with a slight increase in frequency to 1.343 GHz. As the drift tube is then extended into the cavity, the capacity between adjacent drift tubes increases rapidly, thus loading the cavity and dropping both its

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resonant frequency and Q. At the same time, the electric field is lowered more deeply into the interaction space between drift tubes where the accelerating forces are applied to the electrons, and high field intensities appear on the square drift tube nose. By forming the nose to the final wedge-shape, these intensities are reduced, thus reducing the problem of sparking at these points. The final field configuration is shown in Fig. 1D. In Fig. 2 is a plot of the variation in resonant frequency, Q, and ZT^2 for the series just described. Beam loading can be expected to lower the frequency by a few percent. At this point, some small variations in the internal shape of the cavity were made to determine their effect on the measure of performance, ZT^2. It has been found in studying shaped linac cavities,[2] that a significant gain in ZT^2 results from increasing the inner wall radius. The reason for this is that the short field lines in the upper corners of the cavity of Fig. 1D represent higher wall currents and wasted power which rounding these corners tends to reduce. The effect on the field lines for several trial radii is typically as shown in Fig. 3A, in which a round drift tube nose was used, and where the drift tube length was increased slightly with the corner radius to hold frequency nearly constant. The results of this investigation are plotted in Fig. 3B. By increasing the radius to 2-3 cm, a gain of about 5% in ZT^2 can be realized. Further gain requires that the drift tube be formed in the shape of a cone. While these results show that the cavity performance can indeed be improved, the value of shaping the cavity must ultimately be measured against the overall efficiency of the tube. The main point to bear in mind is the value of a computer code such as LALA in predicting performance in a preliminary design and better understanding the operation of the finished product.

The effect of the shape of the drift tube nose on the electric field in the interaction region is summarized in Fig. 4 for cavities displaying approximately the same resonant frequency and Q. It is seen that the round nose has the lowest field intensity, almost 50% lower than the intensity registered at the inside corner of the square nose. The wedge-shaped nose (0.2 cm radius) has one point of high intensity which could be materially reduced by increasing this radius slightly. Naturally, slots in the nose will alter these results.

Analysis of an Internal Cavity Triode

Another tube designed for the Los Alamos proton accelerator is an internal cavity triode (coaxitron) in which the anode structure is suspended in a cavity as shown in Fig. 5A. Pipes for cooling water and voltage connections are located at several points around the toroidal anode. To study this complex structure with the LALA code, it is necessary to idealize the cavity as shown in Fig. 5B and to adjust the code to deal with a higher frequency mode (which still must have no azimuthal variation in electric field). Tests have shown that the discrepancies resulting from these idealizations are not excessive and that the most important computed result, namely operating efficiency, agrees quite well with experimental tests.

Because of the high plate dissipation in this tube, one important investigation with the computer codes was the effect on efficiency resulting from increasing the anode length. A longer anode allows better cooling, but it was uncertain what effect this would have on the electric field in the grid-anode space and ultimately on operating efficiency. A series of computations with LALA was set up, with configurations ranging from the design dimensions of the developed tube with an anode about 6.4 cm long to a test configuration with a 9.8-cm anode. To test these computations, aluminum mockup cavities were constructed for both end points. One mockup configuration duplicated the real asymmetric design as closely as practical, and the other, which employed the elongated anode, was built with idealized cylindrical and axial symmetry. The resonant frequencies were computed with LALA and are shown in Fig. 6 along with the frequencies actually measured in the mockup cavities. The large steps in the computed frequencies for these two end points are due to adjustments made in cavity length and radius in addition to anode length at these points. It can be seen that the frequency measured in the idealized mockup agrees well within 1% with the computed value, but a 4% difference exists between the mockup of the actual tube and its idealized counterpart. This gives a rough measure of the validity of the computed results.

Having completed the resonant frequencies and electric-field distributions for the above range of configurations, the next step was to compute operating efficiency using this information. To do this, another LASL program (COAX) was utilized. This program computes electron current in the tube from the distribution and velocity of charge emitted from the grid into the accelerating electric field of the grid-anode region (found from LALA). The proper phase relation between the current and the rf voltage is then established and the tube efficiency (neglecting the external circuit) is computed in several ways, the most conservative being to divide the power calculated due to current and voltage across the anode surface by the dc power. In Fig. 6, this efficiency computation is applied to the above series of coaxitron configurations operated at rated power (1.25 MW) with a plate voltage and current of 37.5 kV and 89 A, respectively. It is seen that the efficiency remains at about 48% until the anode length is increased by a factor of 50% at which point it begins to fall off. Stated in other words, the anode length could be increased to 9 cm before the rf electric field at the ends of the anode begins to fall off appreciably. This result indicates that a considerably longer anode could be used which would provide improved cooling without sacrificing operating efficiency. These efficiency calculations were made with an assumed plate voltage modulation of 75%. Other levels of modulation were then tried for the idealized final design at full power. The results are shown in Fig. 7 where it is seen that a modulation of 85% actually produces the highest operating efficiency.

Perhaps the most interesting result of the combined LALA and COAX computations is the prediction of operating efficiency for a wide range of power levels. This was done using the V-I plate characteristics of a coaxitron very similar to the final design which has been lab-tested. The measured efficiency from these tests has been reported in Reference 4 and is shown in Fig. 8. The computed efficiencies for several levels of modulation are also shown. Because the computer codes are not limited by practical realities, such as sparking, the computations were made to 60 kV, well above the breakdown potential of the actual tube. The efficiency continues to increase as expected. The computed results bracket the measured results quite well. It is felt, however, that, if the actual modulation level were accurately known and used in the computer codes, the computed efficiencies would be optimistic by 5-10%. This is largely the penalty of the idealizations made which neglect, among other things, energy stored in higher frequency modes not accounted for by LALA.

The electric-field plot shown in Fig. 9 reveals another interesting result. The dark lines locate the points at which the field along the anode side walls is precisely zero in both the final design and for the elongated anode test cavity. These points represent the best positions at which to attach the coolant pipes, anode supports, or anode power leads. While the actual presence of such fittings will effect these positions, they are still a valuable starting point which can shorten the cut-and-try process in tube design.

Acknowledgements

The credit for writing the COAX code which allows computation of coaxitron efficiency goes to R. Thomas and L. W. Mann. Special thanks are due W. F. Rich for his help in applying the LALA code.

References

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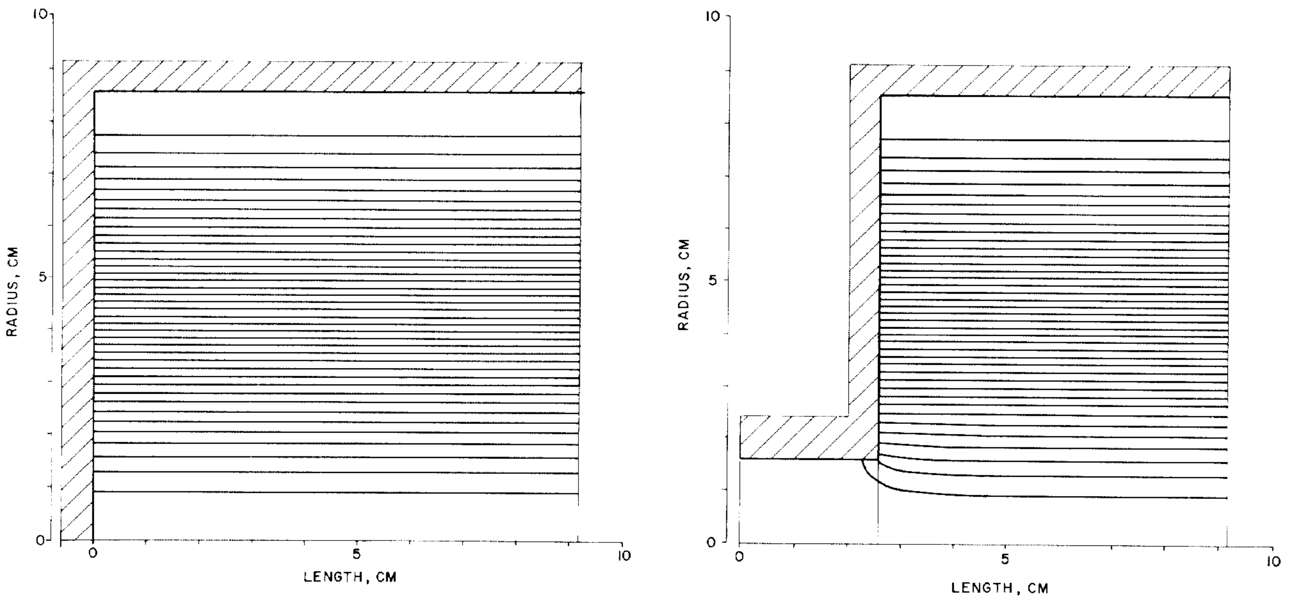
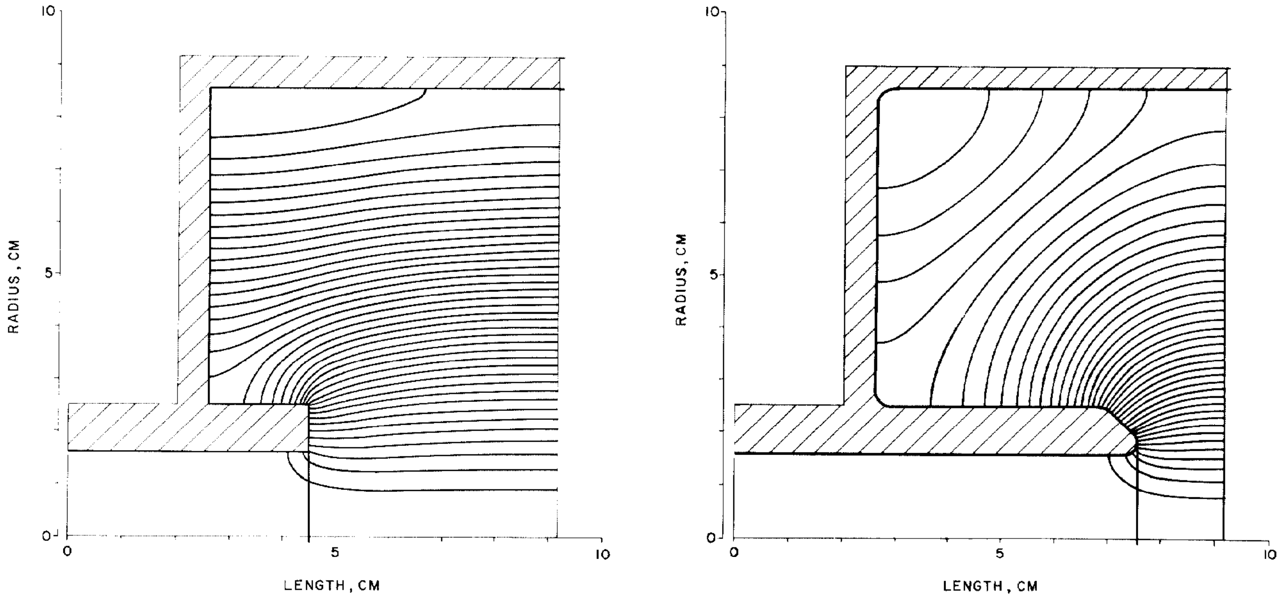


A) RIGHT CIRCULAR CYLINDER

B) ESTABLISH DRIFT TUBE HOLE



C) EXTEND DRIFT TUBE

D) FINAL CONFIGURATION

Fig. 1. Electric-field distributions computed at various stages in arriving at a final klystron cavity configuration.

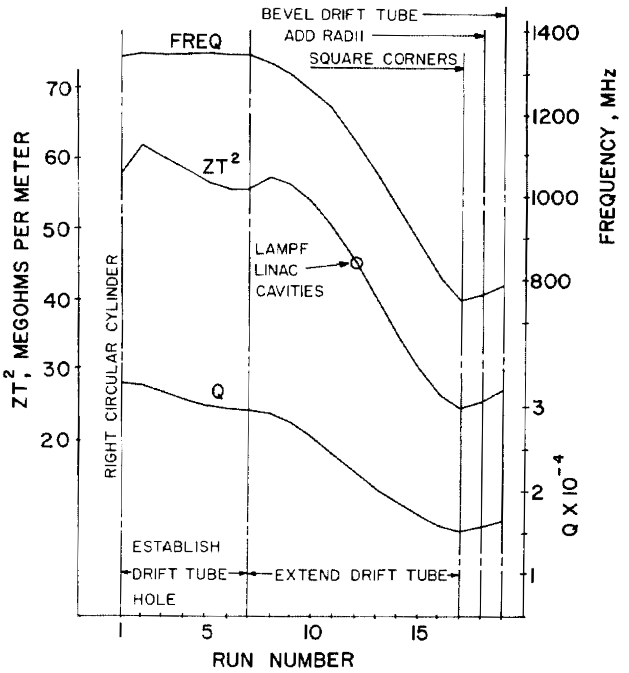
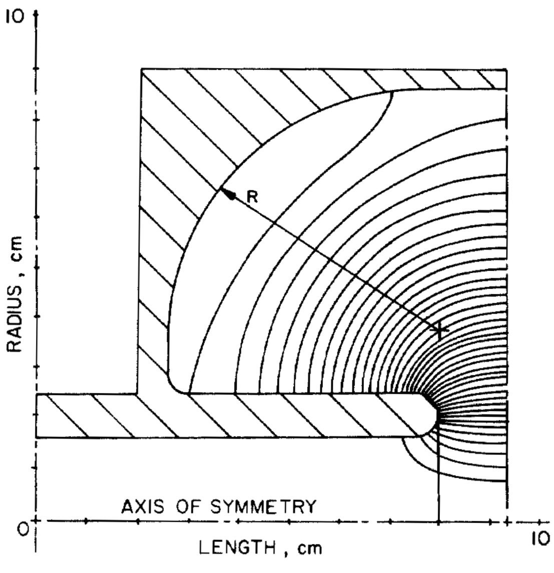
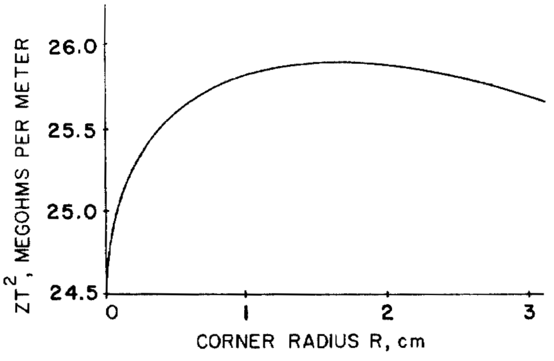


Fig. 2. Operational characteristics computed for klystron cavities ranging from a right circular cylinder to a final design shape.



A) EFFECT OF LARGE CORNER RADIUS ON ELECTRIC FIELD



B) OPTIMIZING ZT^2 BY MEANS OF CORNER RADIUS

Fig. 3. A typical optimization study in which the internal shape of the cavity is altered to improve performance.

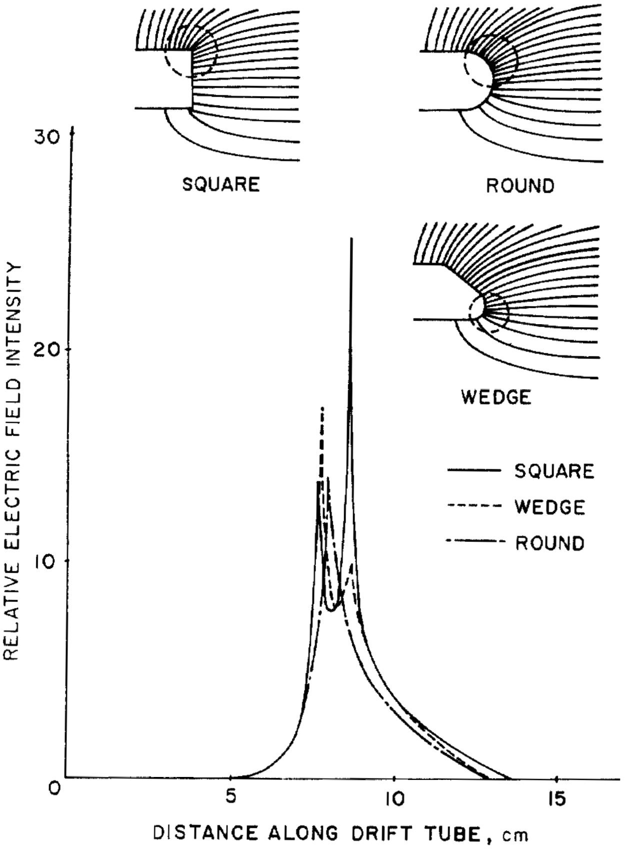


Fig. 4. Relative electric-field intensities along drift tube noses of various shapes.

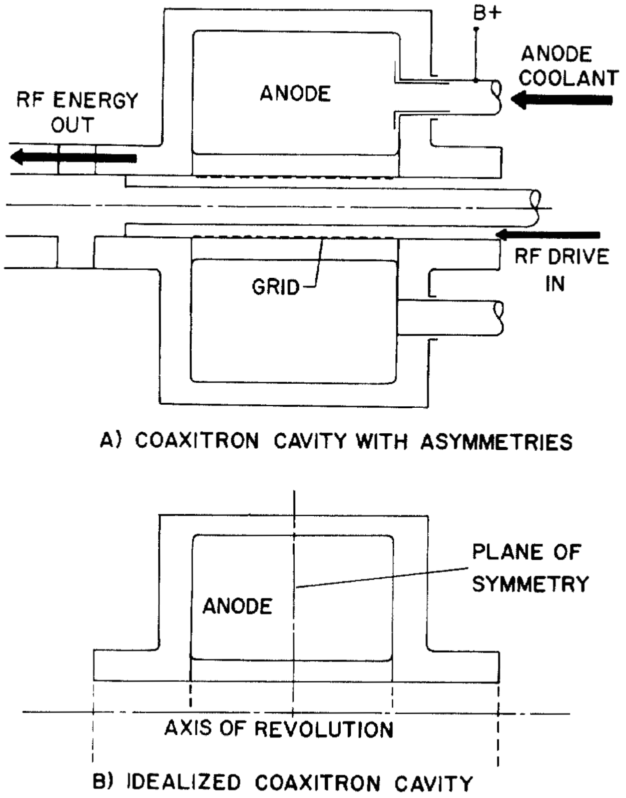


Fig. 5. A typical coaxitron cavity and idealization required for application of the LALA computer program.

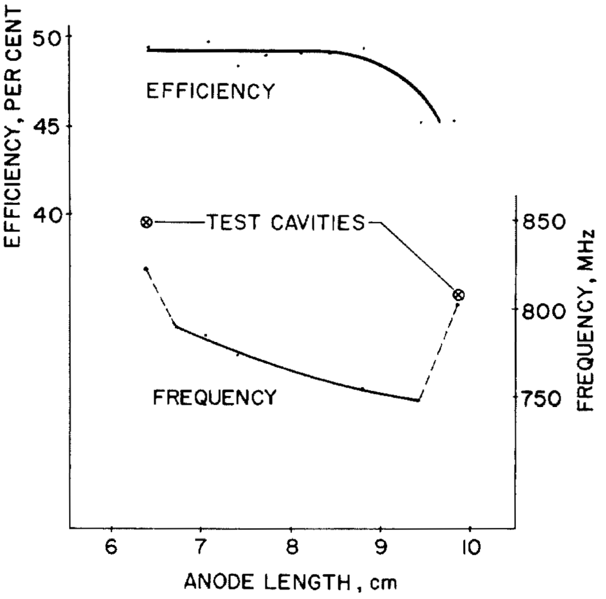


Fig. 6. Computed efficiency and frequency for a series of coaxitron cavities in which anode length is varied.

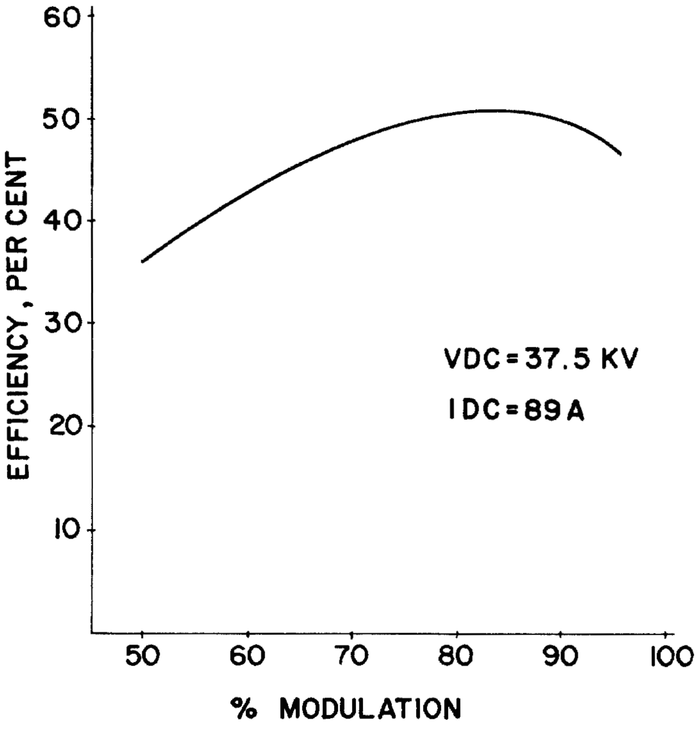


Fig. 7. The effect of anode modulation level on coaxitron electronic efficiency.

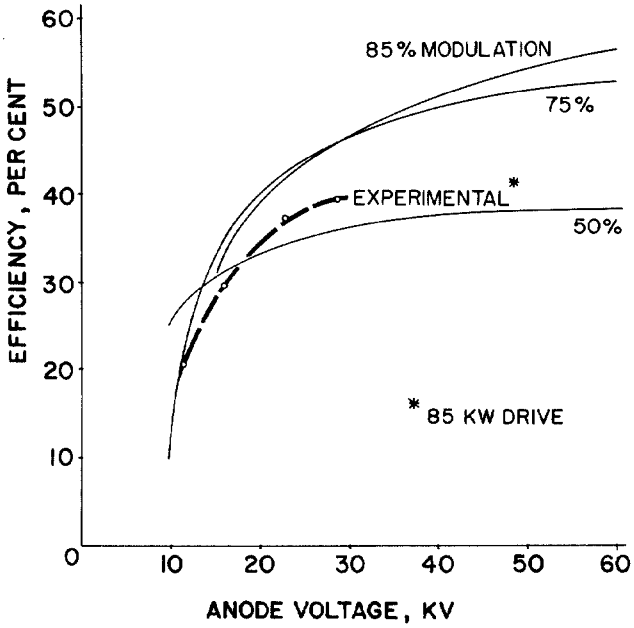


Fig. 8. A comparison of coaxitron efficiencies computed at various modulation levels with experimental results.

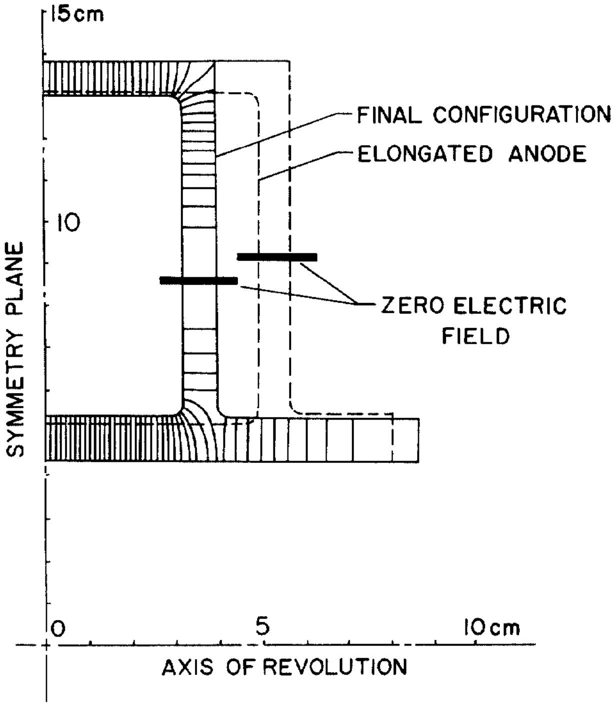


Fig. 9. Positions of zero electric field computed in idealized coaxitron cavities.