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Numerical Analysis of Pierce-Type Electron Guns

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PREVIOUS REPORTS ASSOCIATED WITH THE NRL SOZOTRON

"A 550-Megawatt Pulse Modulator," J.P. Kitchen, D.C. dePackh, H.R.D. Roess, and T.J. O'Connell, NRL Report 6073, Apr. 10, 1964

"Digital Computer Studies of Electron Guns," R.T. Close, NRL Report 6174, Nov. 30, 1964

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ABSTRACT

Digital-computer programs have been used to analyze four Pierce-type electron guns. The numerical analysis has been very successful in identifying the deficiencies of the Pierce-design method when extrapolated to high perveances. It also has been possible to obtain radial phase-space diagrams for the beams from each of the electron guns studied. From these diagrams and by the use of several other computer programs, an estimate of the transverse energy distribution of the electron beams has been made. It has been found that the major contribution to the random transverse energy must be of nonthermal origin.

PROBLEM STATUS

This is an interim report on one phase of the problem; work is continuing on this and other phases.

AUTHORIZATION

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NUMERICAL ANALYSIS OF PIERCE-TYPE ELECTRON GUNS

I. INTRODUCTION

The need for high-quality injected electron beams for the NRL Sozotron project (1) has led to an extensive digital-computer investigation of various electrode structures employed in a variety of existing electron guns. Initial work on this problem employed a slightly modified version of a program originally developed at CERN by Kirstein and Hornsby (2). The methods employed in the K-H program have also been used in several other programs which deal with the same problem (3,4). While the digital-computer method of analysis certainly is a vast improvement over previous methods, certain deficiencies have been noted which must be taken into account in the interpretation of results. During initial work with the K-H program, it was found (5) that while potential and perveance calculations were very good, charge-density and trajectory information was somewhat difficult to interpret. The greatest single feature of concern, however, was the great sensitivity of the problem to initial values and relaxation parameters. For example, it was found that the specified relaxation parameters not only influenced the convergence of the numerical calculation (as they should), but also altered the final results in some cases.

The original K-H program has been modified further in an attempt to correct some of these shortcomings. However, with respect to the convergence problem, the best method still seems to entail a series of short computer runs which serve to uncover suitable input parameters for a given problem. Besides the K-H program, several new programs have been developed which analyze the transverse-velocity distribution of the electron beam as it passes through the electron gun. Such information is of utmost importance to the Sozotron project, since here one strives to obtain a space-charge-limited beam, that is, a beam in which the thermal (random transverse) energy is negligible by comparison with the potential energy of the charge distribution (1). From the output of these transverse energy-analysis programs, phase-space plots can be constructed which give a good picture of beam behavior inside the electrode structure.

In Section II, a short background of previous results is given, the changes to the K-H program are described, and a brief account of several of the new programs developed is given. In Section III, results are given for four electron guns of current interest. These guns are the Eimac 3K 50,000, the gun from a klystron made at Stanford University, the Litton L-3250 and the Litton L-232. The last two of these have been discussed in a previous report (5), but the new calculations are felt to be more accurate and are therefore included. In Section IV, phase-space plots are given for each of the guns mentioned. Section V describes some work which has been done to assign an effective temperature to the beams analyzed. Finally, Section VI concludes the report with a discussion of results.

II. THE PROGRAMS EMPLOYED

As previously noted, programs employing a relaxation type of numerical analysis for the electron-gun problem have been found to suffer somewhat when relaxation parameters are not chosen properly. This difficulty has been effectively, if not satisfyingly, surmounted in the present case by what may be called an experimental method. Here, the skill and experience of the coder coupled with one or more short trial computer runs seems to be successful in determining workable relaxation parameters. In regard to this problem, the general picture is that for low-perveance structures, or rather loose accuracy requirements; the calculations converge quickly to apparently acceptable results with a wide range of parameters. However, as the perveances treated become large (greater than about 2.0×10^{-6}),* or as the accuracy requirements are made more stringent, the calculation must be set with greater care. Finally, if the specified accuracy is extended further, the problem will not converge. This latter difficulty apparently stems from the round-off error inherent in the numerical procedures. It should be mentioned, however, that in every case tried, it has been possible to achieve at least 1-percent specified accuracy in the relaxation calculation.

In previous work, several of the calculated quantities have shown some fluctuations. Double precision arithmetic was introduced at several points in the program in an effort to improve these quantities. In the case of the charge density, however, this procedure did not appear to eliminate the trouble to any great extent. The charge density still seems to suffer from "the discrete nature of the way space charge is introduced ..."(2). The trajectory calculations also were not changed greatly by the double precision arithmetic. This indicated that round-off error could not be blamed for the anomalous behavior of the ray that was traced along the axis of symmetry of the structure. The trouble apparently stems from the part of the program in which the cathode is divided into a specified number of sections. The numerical procedure used will not allow the use of a zero vertical dimension; thus the central ray is not traced from the exact center of the structure but is very slightly displaced. For a spherical-cap cathode, a ray traced from the exact center with no initial velocity would initially be parallel to the horizontal. If the starting point is slightly displaced, however, the initial path is not parallel to the horizontal, and the subsequent path is always in error. It was found that the central ray could be made to follow a more believable course through the structure if a very small flat section was programmed into the cathode boundary curve where it meets the horizontal axis. Fortunately, none of the other calculated quantities exhibited any significant alteration when this procedure was adopted.

The main output of the K-H program is a data tape. It has been found convenient to modify the content of this tape so that it can be used for part of the input for the transverse-velocity-analysis programs. At the present time, there are three separate analysis programs being used. The first of these programs, called DIAGNP, performs calculations based on the minimum of the beam. In most cases, the beams calculated will have well-defined minimum radii, and this program is a useful diagnostic tool. In several instances, however, the beams have not come to well-defined minima within the size of the integration region used, and the results of this calculation are somewhat questionable. The second program, DIAGN2, calculates the radial velocity, longitudinal velocity, and radial position for each ray traced at any given cross section within the integration region. From the output of this program, radial phase-space plots have been constructed, a few of which are shown in Section IV. A third program, PLOT, prepares BCD punched cards for use on an off-line automatic plotter. It is then a fairly simple procedure to obtain accurate trajectory, equipotential, charge density, etc., plots in a minimum of time.

III. COMPUTER RESULTS FOR GUNS OF INTEREST

For each of the four guns considered here, equipotential, trajectory, and cathode-loading plots are given, along with a brief description of typical operating values and other pertinent information.

*Unit of perveance is amps/(volts)$^{3/2}$.

A. Eimac 3K 50,000

The electron gun from the Eimac 3K 50,000 klystron has been used as an electron source for several years in the Electron Beams Branch. It is a solid-beam, convergent-flow structure employing a metal cathode and operating at a perveance of about 1.0×10^{-6}. This gun is a good example of a Pierce-type structure (6). The Pierce theory is expected to be valid, at least approximately, at this value of perveance. In typical experiments, the 3K 50,000 has been operated at about 30 kv and has produced currents of about 5 amperes. The computer investigation of this structure obtained a perveance value of 0.994×10^{-6}, which agrees well with experiment. The current density at the cathode surface, or cathode loading (Fig. 1), is very uniform. The small fluctuations in the cathode-loading plot are probably due to the program itself and not to any physical phenomena. The general appearance of the plot indicates that a slight degradation in cathode loading occurs at the edge of cathode, while maximum values are attained at the center. It will be seen that this behavior is just the opposite of that in higher-perveance structures, where minimum values are found near the center and maximum values at the edge. The equipotential plots (Fig. 2) show just a slight distortion at the anode hole, which accounts for the very uniform cathode loading. The beam trajectories (Fig. 3) are seen to be quite laminar, and one expects good-quality beams from this gun. In general, the 3K 50,000 appears to be a well-designed, rugged structure, suitable for low-energy beam experiments. Although additional electronics are required for the metal cathode, the fact that vacuum requirements are lessened provides a distinct advantage compared to the requirements of oxide-coated cathodes. Due to its good overall characteristics, this gun provides a standard of comparison for the other guns investigated, which are all Pierce-type structures designed for higher perveance values.

B. The Stanford Gun

An electron gun similar to that used on the klystrons that drive some of the early Stanford linear electron accelerators has been available to this group for some time. This gun is a solid-beam, convergent-flow structure employing an oxide-coated cathode and designed for a perveance of 1.25×10^{-6} (7). The computer investigation indicates that this value of perveance is somewhat high, the calculated value being slightly less than 1.0×10^{-6}. Many experiments with this gun also indicate that 1.0×10^{-6} is the value to be expected. Initial interest in this structure derived from its ability to produce a beam of very high current. The design figures of 250 amperes at 400 kv have not been attained at NRL, the maximum experimental values being about 150 amperes at 300 kv. Realization of higher currents and energies was hampered initially by vacuum problems and later by internal breakdown. This gun is not being used at the present time, although it may be in the near future. The cathode-loading plot (Fig. 4) is fairly uniform, and, again disregarding the small fluctuations, one notices that the general tendency is for maximum loading at the edge with the minimum current density at the center. The equipotential graph (Fig. 5) shows slightly more distortion at the anode hole than with the 3K 50,000. The trajectory plot (Fig. 6) indicates a laminar flow, but it should be noticed that the outermost rays are intercepted by the anode structure. Beam transmissions through the anode of the order of 93 percent have been measured, and the computed value is in rough agreement, although somewhat higher. This discrepancy probably stems from the fact that thermal effects are neglected in the program. Another interesting property of this beam is that it is still converging at the end of the region of calculation. The region was extended some 30 percent in other computer runs, but the beam still appeared to be converging. Thus, one expects that the beam minimum is reached well beyond the anode. This fact was discovered experimentally some time ago, when it was found that no additional focusing was needed to collect the beam at the end of a long 1-1/8-in. I.D. tube. The Stanford gun is found to be a very satisfactory electron source for currents in excess of 100 amperes. Physically, the gun is a massive structure and somewhat more difficult to handle than several higher-perveance guns which give about the same magnitude of

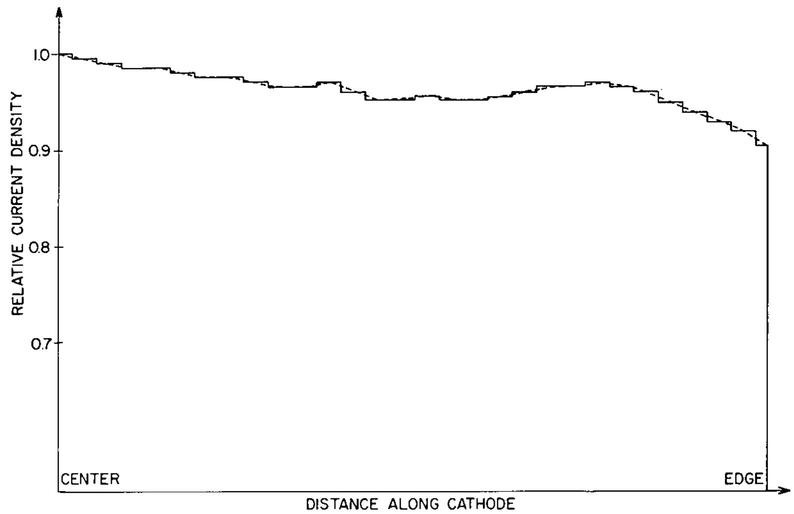


Fig. 1 - Cathode-loading plot for Eimac 3K 50,000 electron gun

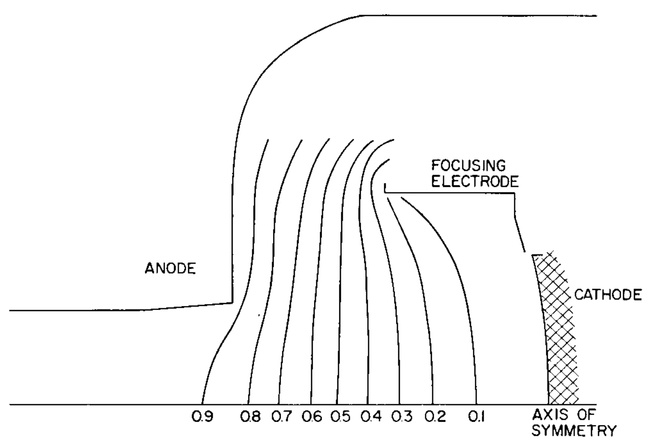


Fig. 2 - Equipotentials for Eimac 3K 50,000 electron gun

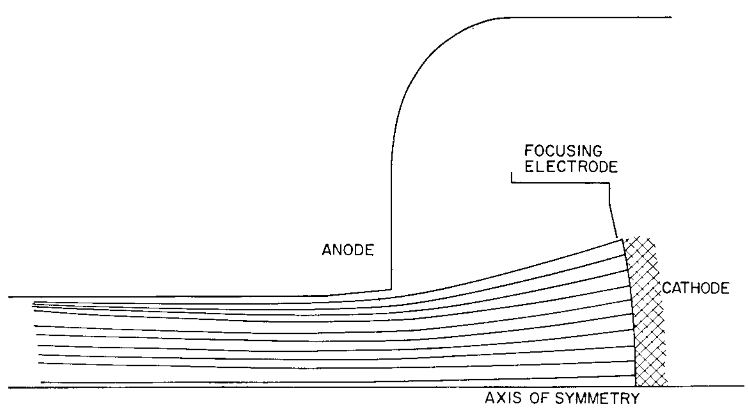


Fig. 3 - Trajectory plot for Eimac 3K 50,000 electron gun

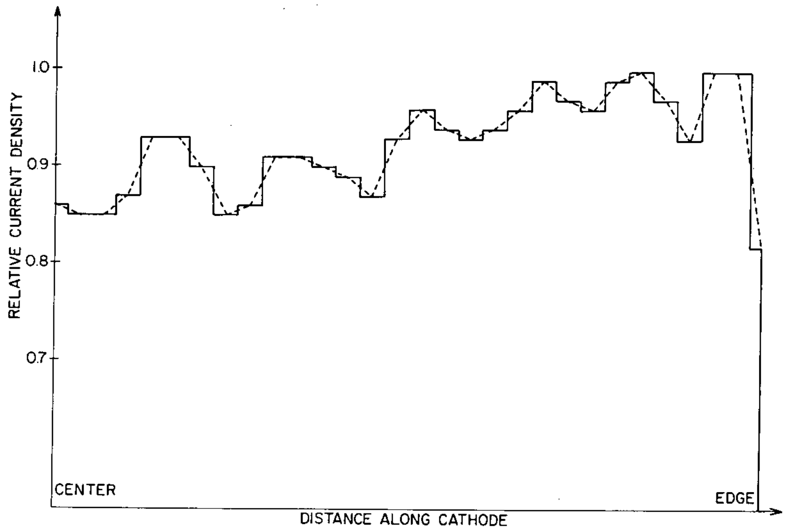


Fig. 4 - Cathode-loading plot for Stanford University electron gun

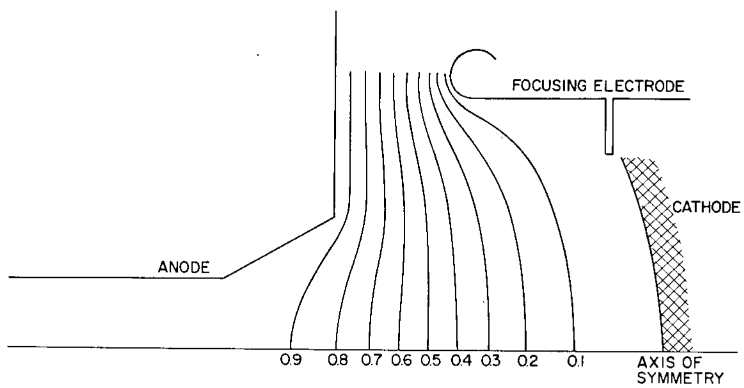


Fig. 5 - Equipotentials for Stanford University electron gun

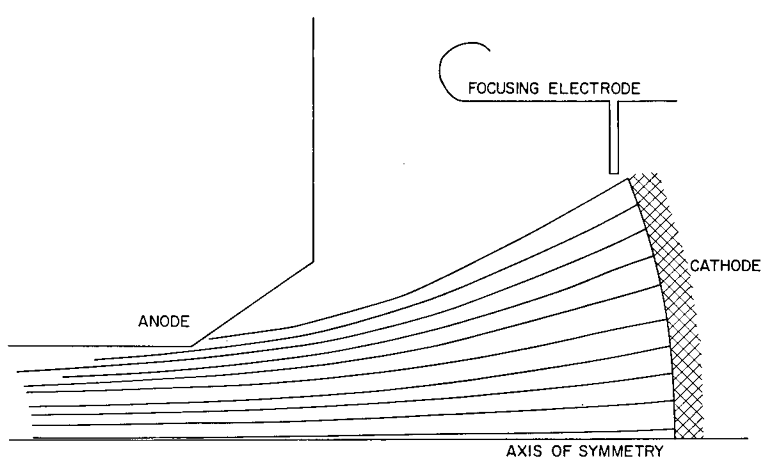


Fig. 6 - Trajectory plot for Stanford University electron gun

current. The particular gun in use here incorporates a demountable anode which allows one to recoat the cathode surface if vacuum trouble develops. This procedure, although simple in principle, is somewhat difficult because of the size and weight involved.

C. The Litton L-3250

The electron gun from the Litton L-3250 klystron has been used on the first model of the NRL Sozotron. It is a solid-beam, convergent-flow gun employing an oxide-coated cathode. The L-3250 was designed by the Pierce method for a perveance of 2.0×10^{-6}. In practice, it has been reported capable of operating at a value of 1.8×10^{-6}. However, the computer investigation and experimental work here indicate that a value nearer 1.6×10^{-6} is to be expected. It has also been reported that the gun can be run at voltages greatly in excess of its quoted typical value of 185 kv. Currents of over 100 amperes have been consistently obtained with this gun. The cathode-loading plot (Fig. 7) shows a marked depression at the center of the cathode. This behavior is expected in spherical-cap cathode guns designed by the Pierce method for high perveance and is usually attributed to the anode-hole effect. The equipotential plot (Fig. 8) shows the distortion caused by the anode hole. The trajectory plots (Fig. 9) indicate several crossovers, especially near the beam boundary beyond the anode hole. The flow therefore cannot be characterized as laminar, although it is not extremely bad. One notices here evidence for the breakdown of the Pierce method at high perveances. The cathode loading becomes nonuniform, the flow characteristics deteriorate, and the equipotentials exhibit large distortions in the vicinity of the anode hole. The L-3250 is much easier to handle than the Stanford gun, for example, due to its lower voltage requirements, smaller physical size, lighter weight, and its improved thermal coupling from heater to cathode. Its use then involves a bit of a compromise between ease of handling and the better beam quality of lower-perveance structures.

D. The Litton L-232

The Litton L-232 electron gun is a specially designed model reported capable of producing a current of 1000 amperes. It is an adaptation of the gun used on the Litton L-3403 klystron to higher voltages. The L-232 is a solid-beam, convergent-flow type also employing an oxide-coated cathode and designed to operate at a perveance of 2.5×10^{-6}. The computed value of perveance, 2.42×10^{-6}, is slightly less than the design value. Early experimental work indicates that at high voltages, the perveance is definitely lower than the 2.5×10^{-6} figure. These early experiments have obtained currents up to 890 amperes at 540 kv.* A possible factor arising here is the relativistic correction that should be applied. Below 511 kv, one may use the approximate formula (8)

$$G = G_o \left(1 - \frac{3}{28} \frac{ev}{mc^2}\right) \quad (1)$$

where G is the perveance, G_o is the nonrelativistic perveance, v is the voltage applied to the anode, e is the magnitude of electronic charge, and mc^2 is the rest energy of the electron. Simple considerations therefore indicate that a correction in excess of 10 percent may be applied to the design value. The cathode-loading plot (Fig. 10) shows the characteristic central depression expected, and the equipotentials (Fig. 11) show a large distortion at the anode hole. The trajectory plots (Fig. 12) exhibit many crossovers, but again the flow does not appear grossly inferior to lower-perveance structures. The L-232 was reportedly designed using a resistance-board analog device (9) to improve on the basic Pierce design. However, the same general features of Pierce designs extrapolated

*Private communication from J.P. Kitchen and T.J. O'Connell of NRL.

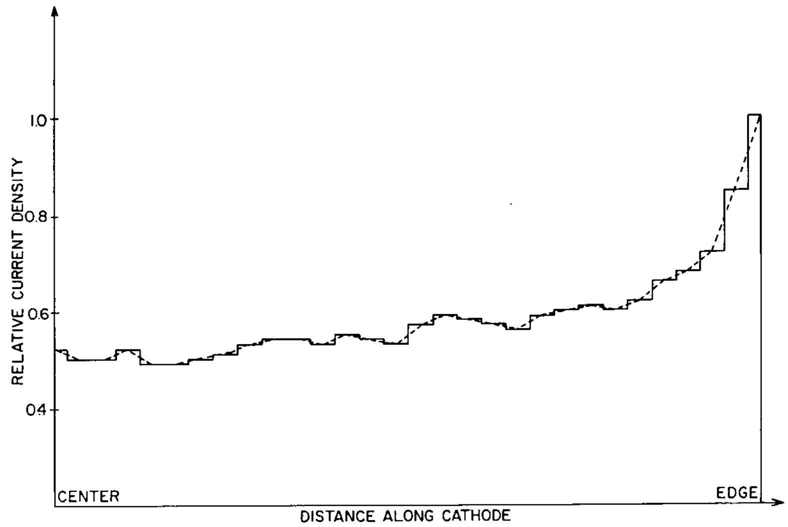


Fig. 7 - Cathode-loading plot for Litton L-3250 electron gun

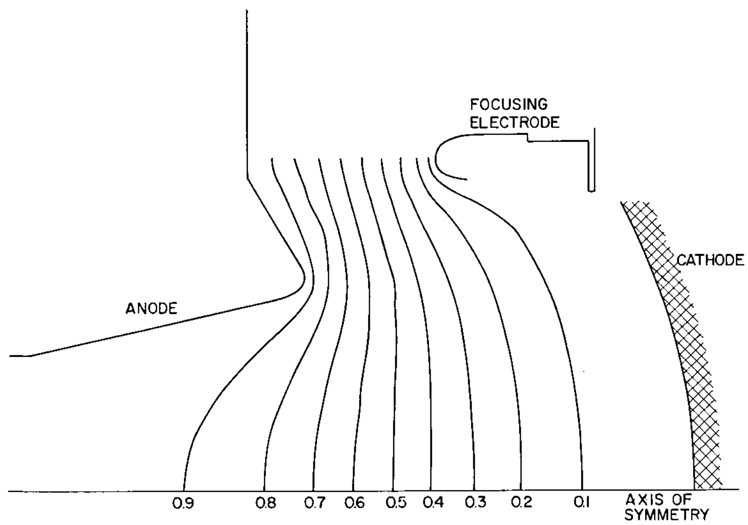


Fig. 8 - Equipotentials for Litton L-3250 electron gun

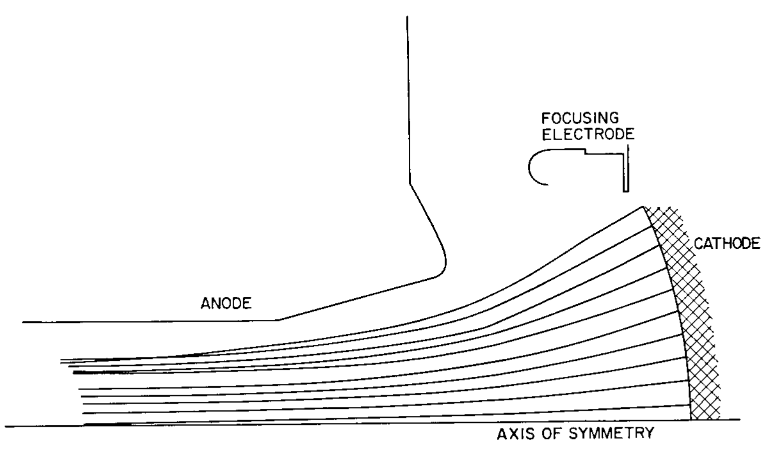


Fig. 9 - Trajectory plot for Litton L-3250 electron gun

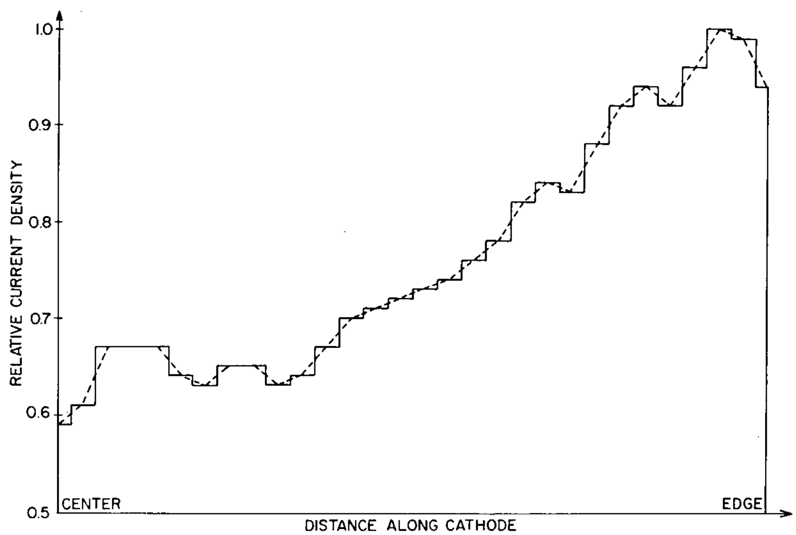


Fig. 10 - Cathode-loading plot for Litton L-232 electron gun

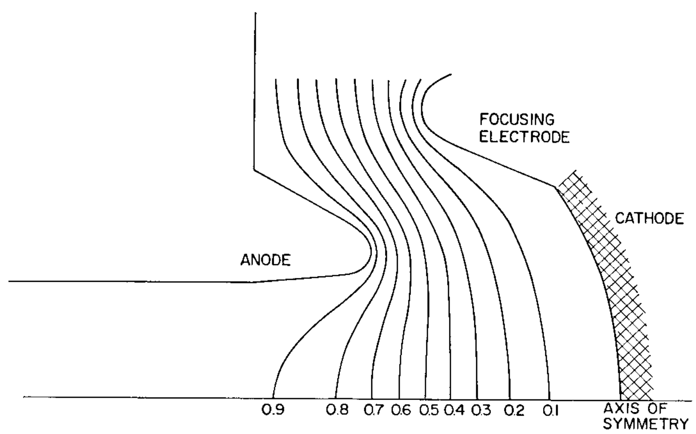


Fig. 11 - Equipotentials for Litton L-232 electron gun

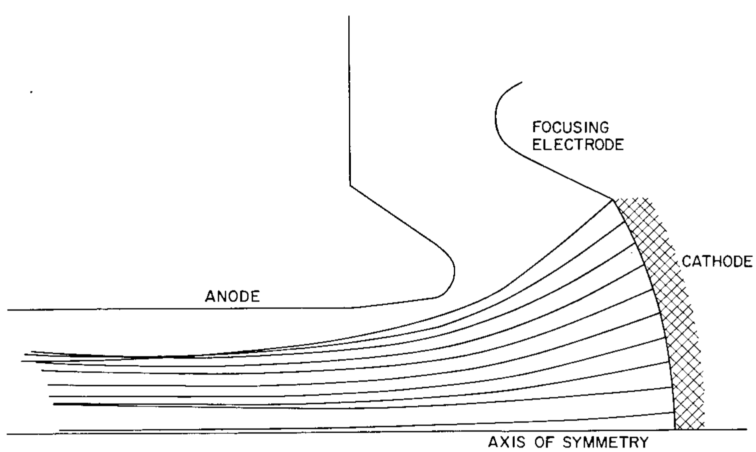


Fig. 12 - Trajectory plot for Litton L-232 electron gun

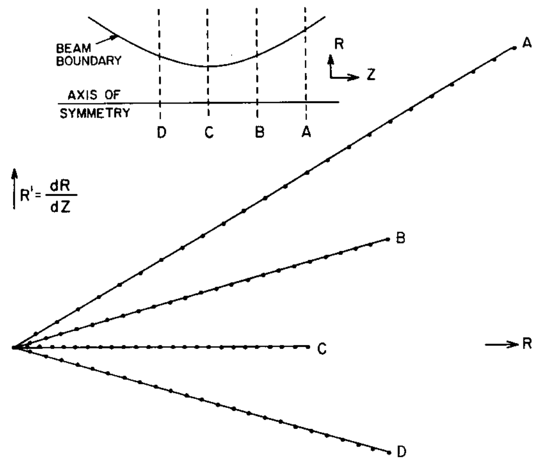


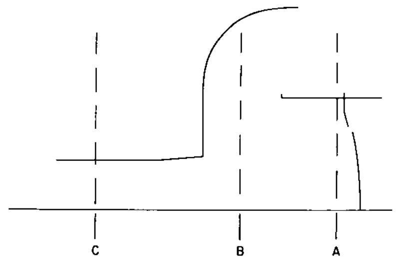
Fig. 13 - Radial phase space diagrams to be expected from a model laminar-flow electron beam at cross sections before attaining a minimum radius A, B; at the minimum C; and beyond the minimum D

to high perveance are still very much in evidence. Interest in the gun of course stems from the huge currents it is possible to generate. Again, use of this gun involves a compromise, here between magnitude of beam current and beam quality. Some benefit may be derived by judicious redesign of focusing optics, etc., but great improvement in beam quality is not likely using this basic design.

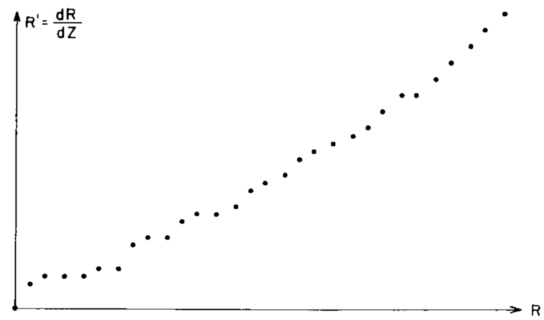
IV. PHASE-SPACE DIAGRAMS

For a uniform, laminar beam moving with constant longitudinal velocity, a phase-space diagram like Fig. 13 would be expected. In this diagram, $R' = dR/dz$ is plotted against R for a cylindrically symmetric beam, reaching a minimum radius and then expanding, where R and z are cylindrical coordinates. Since the beam in this ideal situation is laminar, the radial velocity at a given cross section is directly proportional to the radial position. Thus, the idealized phase-space diagram simply consists of points which lie along straight lines. From the computer results, it has been possible to construct radial phase-space diagrams for each of the guns discussed previously (Figs. 14 through 17). It is apparent that the behavior of the computed beams is markedly different from the ideal case. At axial positions corresponding to cross sections far from the anode aperture, the points do lie approximately on straight lines. However, as the beam progresses through the gun structure, large deviations from the straight-line plots are noted. As expected, the deviations are greater in the higher-perveance structures, but it will be noted that significant distortion is apparent to some extent in all the guns analyzed.

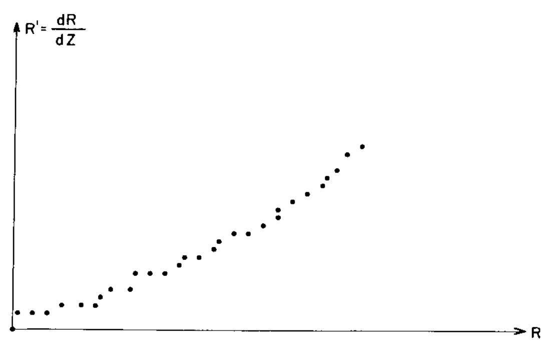
Certain general features of these computed diagrams are noteworthy. The most striking feature, in most cases, is the development of a "hook" in the diagram at the edge of the beam at cross sections near the anode aperture. This behavior is caused no doubt by aberration in the anode aperture lens. Thus, the largest distortion is seen to be roughly confined to the beam boundary. It appears, then, that some hope of improving beam quality at the expense of beam current is offered by the use of apertures which intercept the outer portions of the beam after it passes through the anode. Two points should be indicated in this regard. First, the higher-perveance beams have a nonuniform current-density distribution, with the larger values occurring at the beam edge. If apertures are used with such guns, the current intercepted may, in fact, become so great that little is gained by employing the high-perveance structure in the first place. Second, it should be remembered that an aperture (the anode aperture) is the essential cause of the beam distortion. Thus, careful design is indicated if additional apertures are to be added to the system.



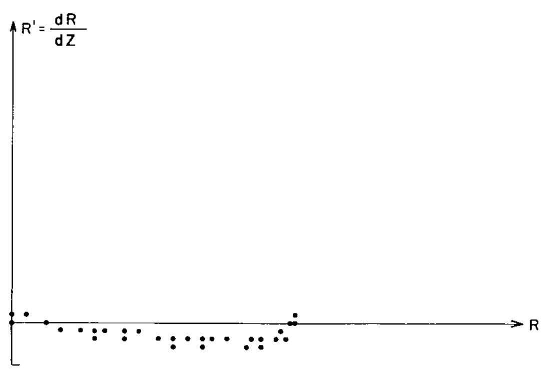
a. Electrode structure with cross sections A, B, C noted



b. Phase-space diagram at cross section A

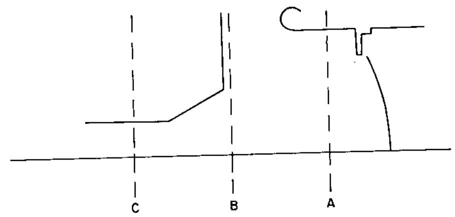


c. Phase-space diagram at cross section B

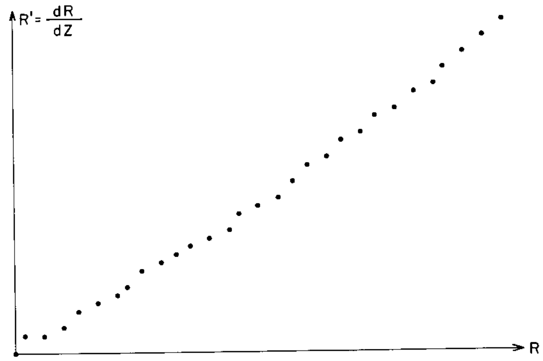


d. Phase-space diagram at cross section C

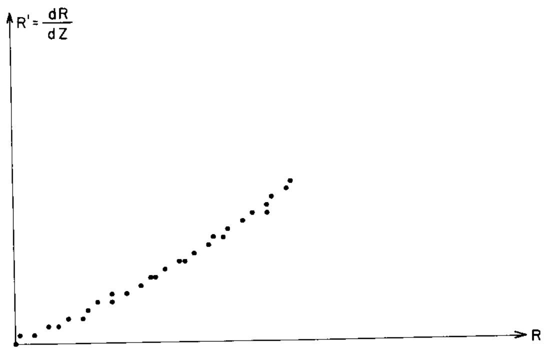
Fig. 14 - Eimac 3K 50,000 radial phase-space diagrams



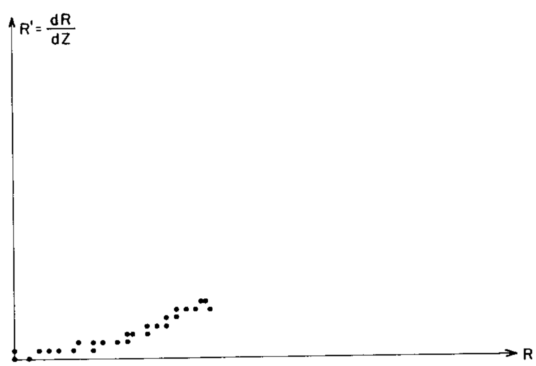
a. Electrode structure with cross sections A, B, C noted



b. Phase-space diagram at cross section A



c. Phase-space diagram at cross section B



d. Phase-space diagram at cross section C

Fig. 15 - Stanford radial phase-space diagrams

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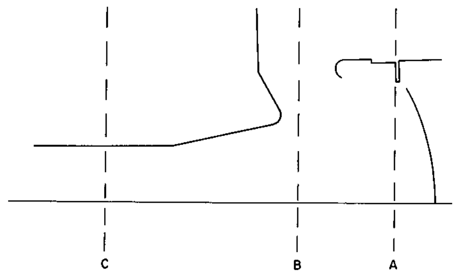
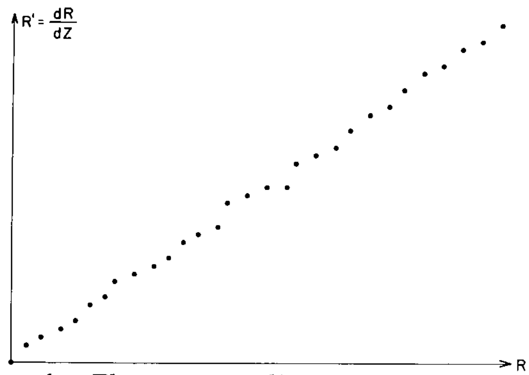
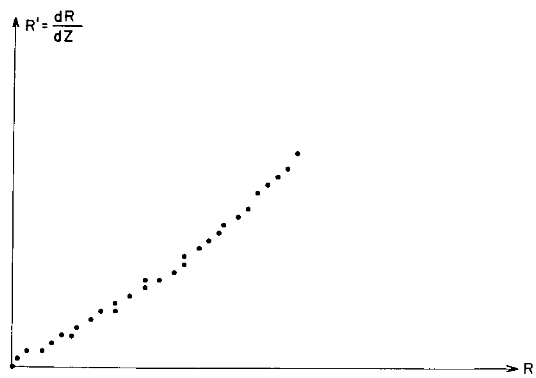


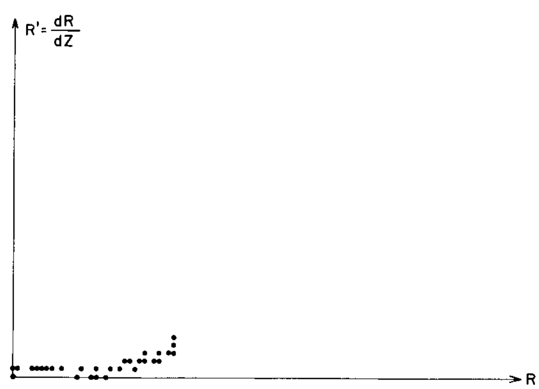
a. Electrode structure with cross sections A, B, C noted



b. Phase-space diagram at cross section A

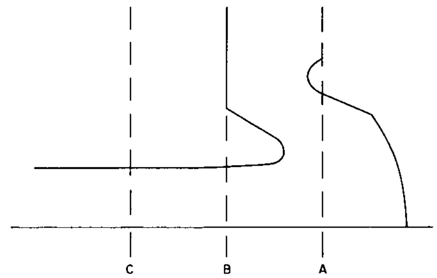


c. Phase-space diagram at cross section B

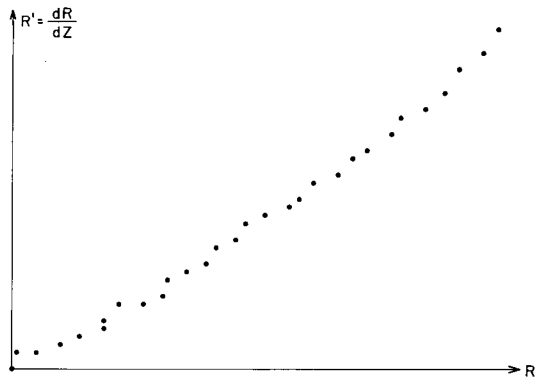


d. Phase-space diagram at cross section C

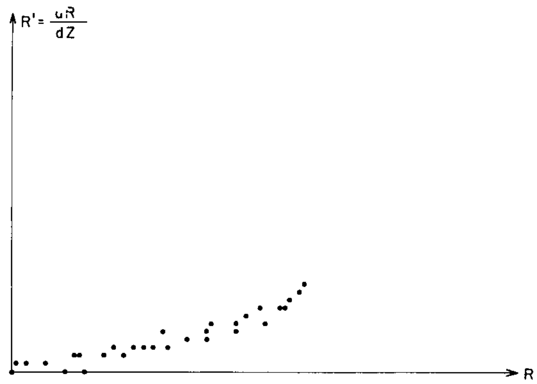
Fig. 16 - Litton L-3250 radial phase-space diagrams



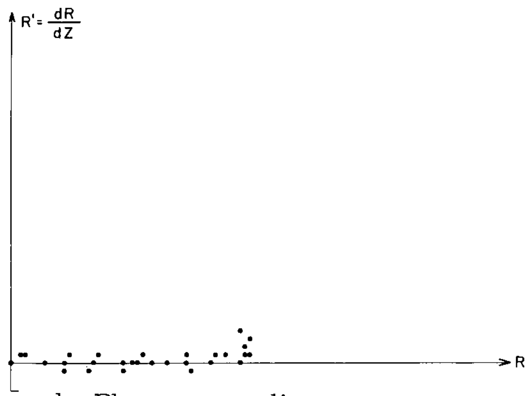
a. Electrode structure with cross sections A, B, C noted



b. Phase-space diagram at cross section A



c. Phase-space diagram at cross section B



d. Phase-space diagram at cross section C

Fig. 17 - Litton L-232 radial phase-space diagrams

Another striking feature of the computed phase-space diagrams is the very great dependence of the final configuration on initial values. If a certain ray is found to depart slightly from a supposed straight-line diagram at cross sections far from the anode, this same ray will be found to exhibit very large departures at cross sections near the anode hole and beyond. Also, if the cathode-boundary curve is altered slightly, very different phase-space plots are found to result. This behavior is somewhat like that of a real beam when initial electron velocities are considered. In this case, a general consideration of Liouville's theorem (6) leads one to define an effective temperature which is inversely proportional to the square of the beam radius. In the case of the computed beam, it also should be possible to assign an effective temperature on the basis of the deviations from idealized situations. In fact, by slightly varying the cathode boundary curve (using variations that are well within manufacturing tolerances), the calculated beams can be given initial temperatures and their subsequent behavior studied. This argument is at the present time rather qualitative, but some numerical calculations have been carried out. These are described in the next section.

V. EFFECTIVE BEAM TEMPERATURES

Several methods can be devised for the assignment of an effective beam temperature. The method described here is based on an analysis of the beam minimum radius. For a laminar beam, one would expect that at the beam minimum the radial-velocity content of the beam would vanish. The numerical procedure adopted in this case first calculates the minimum radial position of each ray traced through the electrode structure. Then a weighted average of these radii is found which defines a mean minimum radius of the beam. The radial velocity of each ray at this mean minimum radius of the beam is then calculated. The simplest assumption is that the effective beam temperature is proportional to the squares of the computed radial velocities. While certainly this argument is rather crude, it appears that other methods of calculation give approximately the same order of magnitude for the effective beam temperature. All of the structures analyzed seem to obey a relation of the form

$$E_{trans} = KE_o$$

where E_{trans} is the energy associated with the transverse beam motion and E_o is the energy of directed motion (essentially the applied voltage). The proportionality constant K is always of the order of 10^{-4}, but unfortunately the crude method of calculation does not allow a valid comparison of the various guns analyzed at this time. The relation between E_{trans} and E_o is unfortunate for applications requiring a low transverse beam temperature, since it implies that large transverse energies are to be expected from high-energy beams. Moreover, this relation indicates that the main "temperature" effect is of nonthermal origin. One must attribute the effective beam temperature primarily to the inherent design (or lack thereof) of the focusing structure.

As an example, consider a cathode operating at 1000°K and a beam-area compression ratio of 10 (typical of the high-perveance structures treated here). On the basis of Liouville's theorem, an effective temperature of about 1 ev would be expected irrespective of the applied voltage. Here, the calculations indicate that for a gun operated at 100 kv, an effective temperature of the order of 10 ev is to be expected. Experimental estimates of beam temperature have been made by considering the skirt width of beam profiles measured with a Faraday cup-type beam tester (10). The results obtained from the procedure are in good agreement with the numerical result found here.

VI. DISCUSSION

Although the computer investigation of these electron guns has provided much useful information, several facts should be kept in mind. The analysis is still nonrelativistic, and only approximations to the behavior of high-energy beams can be made on this basis. Although relativistic correction formulas are available (e.g. Eq. 1) these, for the most part, have been derived without consideration of magnetic effects and are therefore not self-consistent. Also, the result of introducing initial electron velocities into the analysis has not been studied in detail. Certainly, the transverse velocity programs can provide an effective temperature determination, but without detailed study of the initial velocity spectrum these results are again only approximations. It may be mentioned that Kirstein (11) has carried out an analysis of the thermal-velocity effect using an expanded version of the original K-H program. His procedure is much more sophisticated than the approach outlined in this paper.

VII. ACKNOWLEDGMENTS

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Digital-computer programs have been used to analyze four Pierce-type electron guns. The numerical analysis has been very successful in identifying the deficiencies of the Pierce-design method when extrapolated to high perveances. It also has been possible to obtain radial phase-space diagrams for the beams from each of the electron guns studied. From these diagrams and by the use of several other computer programs, an estimate of the transverse energy distribution of the electron beams has been made. It has been found that the major contribution to the random transverse energy must be of nonthermal origin.

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