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Summary

Computational procedures are reported for treating power losses due to secondary electrons in multistage depressed collectors (MDC) for traveling-wave tubes (TWT) and other O-type electron tubes. the MDC is modeled with an advanced, multidimensional computer program. Representative beams of secondary electrons are then injected at the points of impact of the primary beams. Separate programs are used to calculate representative beams of high-energy primary electron beams and of low-energy true secondaries. The recomputation of the MDC model including the true secondary beams allows determination of the secondary emission losses, and, if necessary, redesign of the MDC to improve performance. Recomputation of the MDC model including the primary beams is used to check on possible backstreaming from the MDC to the RF interaction structure of the tube. A comparison with experimentally measured values of TWT and MDC efficiencies is made.

Introduction

Traveling-wave tubes (TWT's) are widely used as microwave amplifiers because of their high power capabilities and high efficiencies—especially when equipped with multistage depressed collectors (ref. 1). A TWT consists of (1) an electron gun, which creates an electron beam; (2) a radio-frequency (RF) interaction structure, in which the electron beam interacts with a radio-frequency signal, with part of the electron beam's kinetic energy converted to radio-frequency energy; and (3) a collector, in which the electron beam is absorbed.

At the end of the RF interaction structure, the electron beam still has most of its initial kinetic energy, which should be recovered for maximum efficiency. Most of the kinetic energy can be recovered by operating the collector elements at negative potentials relative to the RF interaction structure. Because of the spread in electron kinetic energies, the use of three to five stages at different potentials allows more energy to be recovered than would a single potential.

In designing a multistage depressed collector (MDC) it is important (1) to keep electrons from flowing back from the collector into the RF interaction structure, where they can cause oscillations, and (2) to collect the electrons at the lowest possible potential, to recover as much energy as possible. Current design (refs. 2 and 3) methods allow one to design an MDC on the basis of the primary electron beam that leaves the RF interaction structure. However, this does not treat the effects of secondary electrons emitted from the electrode surfaces by the impact of the primary electrons. This report presents a method of including the effects of these secondary electrons in the design of an MDC.

Methods

All collector design calculations were done with the program by Herrmannsfeldt (ref. 4). The program reads a dataset containing the design of the collector and the set of initial electron beam conditions. The program assumes an axisymmetric collector design, so all positions are given by a radial coordinate R and by an axial coordinate Z. The electron beam is divided into a number of elements, and initial conditions for each are read in. These initial conditions consist of (1) a number identifying the electron beam element, (2) an initial position, R and Z, (3) an initial kinetic energy of the electrons in the element, (4) an initial direction of motion relative to the Z-axis, (5) the current carried, and (6) the initial kinetic energy of angular motion of the electrons in the element. With this information the Herrmannsfeldt program computes the potential distribution within the collector and charts the charge trajectories. A typical collector design is shown in figure 1.

Knowledge of where the current is collected allows one to determine the collector efficiency and change the geometry and/or the collector voltages so as to optimize the efficiency. Only recently has the primary beam current been analyzed and any effects that come from secondary emission have not been included in the model.

Secondary electrons are emitted over a large range of angles and energies. They can be divided, however, to a good approximation, into true secondaries, which leave the surface at low energies (0 to 50 eV), and reflected primary electrons, which leave the surface with approximately the same energy as that of the incident primary electrons (ref. 5). For each type our present calculation uses the Herrmannsfeldt program with additional (secondary) electron beam elements included in the dataset. Because the two types of secondaries have different effects on collector design, a separate program is used for each type to calculate the input parameters for these additional elements.

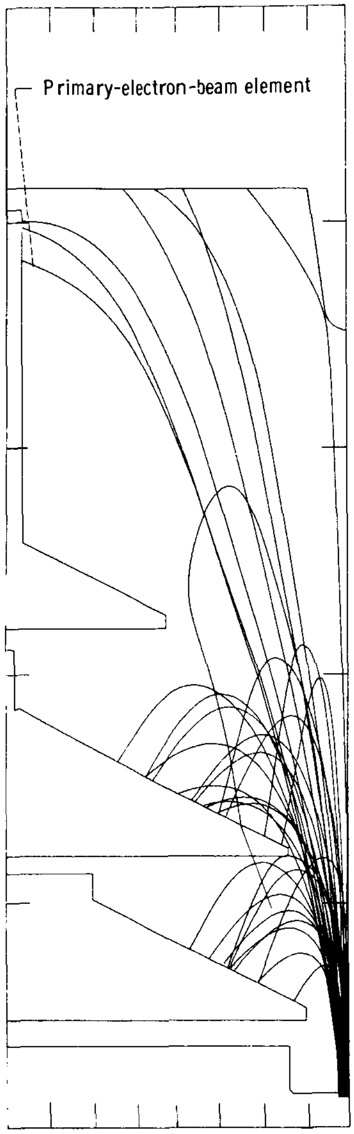

Figure 1.—Typical collector design with primary-electron-beam trajectories.

The Herrmannsfeldt program is first run with only the primary electron beam included. The program outputs the final positions and trajectories of each electron beam element. These are stored in a dataset for use in the calculation of the initial conditions of the secondary-electron-beam elements.

True Secondaries

The secondary-electron-beam input parameters are calculated from the final positions and trajectories of the primary electron beam, as calculated by the initial run of the Herrmannsfeldt program, by setting the angle between the Z-axis and the true secondary-electron beam equal to the negative of the angle between the final trajectory of the primary-electron-beam element and the Z-axis. The Herrmannsfeldt program outputs the final position of the electron beam at the point where the program first determines that the beam is inside an electrode. However, the program requires a starting position for the secondary-electron beam outside the electrode. Therefore, a starting position for the secondary-electron beam is determined by moving it from the final position of the primary-electron beam, sufficiently far in a direction opposite to the final motion of the primary-electron beam, so that its new position is outside the electrode. (Two grid units have been found to be sufficient.) This position is then expressed in terms of the *R* and *Z* coordinates. An initial kinetic energy of 10 eV is assumed. (Because of this low initial kinetic energy, the initial direction assumed for the secondary-electron-beam element has little effect on the trajectory of the secondary-electron-beam element.) The kinetic energy of angular motion is assumed to be zero. The current in the secondary-electron-beam element is set at

$$I_s = I_p C_s (1 + 0.5\,\theta^2)$$

where

I_s secondary-electron-beam element current, A

I_p primary-electron-beam element current, A

C_s coefficient of secondary electron emission for the surface (typical values, 0.8 for Cu, 0.4 for graphite, and 0.2 for textured carbon)

θ angle of the incident primary-electron-beam element from the normal, radians

(This formula approximately incorporates the typical angular dependence of true secondary electron emission.)

After the input parameters for the secondary-electron-beam elements have been calculated, they are incorporated into the dataset for the Herrmannsfeldt program, which is then rerun. Usually this is sufficient. Occasionally the primary-electron-beam element trajectories are significantly modified by including the secondary-electron-beam elements. In most cases the problem is solved by repeating the calculation with the final positions and trajectories of the primary-electron beam elements. Where this does not solve the problem, it is necessary to repeat the calculations a number of times, slowly increasing the secondary-electron-emission coefficient between runs, and recalculating the initial positions and trajectories of the secondary-electron-beam elements each time on the basis of the final conditions of the primary-electron-beam elements from the previous run.

TABLE I.—COMPARISON OF MDC AND TWT EFFICIENCIES

	Efficiency, percent	
	Without secondaries	With secondaries
MDC	84.9	83.7
TWT	62.2	61.0

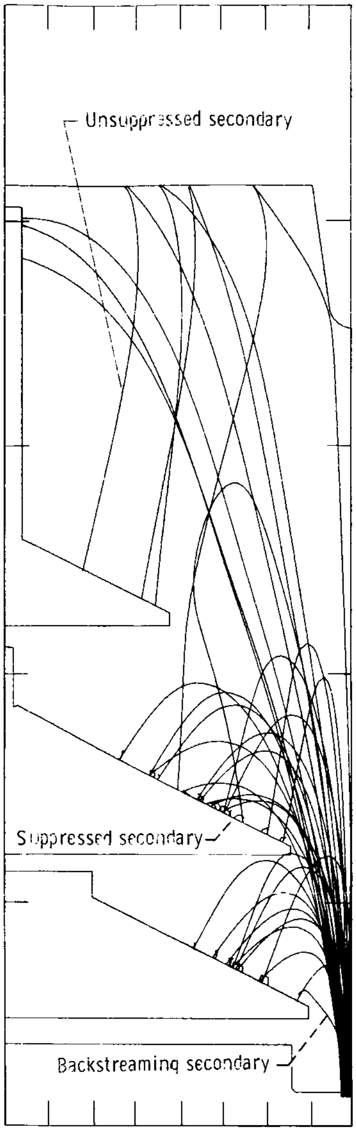

Figure 2.—Typical collector design with true secondary-electron-beam trajectories included.

The results of a typical calculation are shown in figure 2 where (1) a backstreaming secondary, (2) unsuppressed secondaries, and (3) suppressed secondaries are represented. Table I compares the tube and collector efficiencies calculated with and without considering secondaries.

Reflected Primaries

The calculation for reflected primaries are similar to those for true secondaries. They differ, however, in a few of the assumptions used. It has been assumed for the case of the reflected primaries that the initial direction of the reflected-primary-beam element will be reflected at equal angles to the normal, although other assumptions would be equally useful. The starting positions for the reflected primary-electron beams are determined like the starting positions of the true secondary-electron beams. An initial kinetic energy equal to the final kinetic energy of the primary-electron-beam element is assumed. The reflected-primary-beam element is assigned a kinetic energy of angular motion of zero. The current is found by using the formula:

$$I_r = I_p 0.005$$

where

I_r reflected primary electron current, A

I_p primary electron current, A

(The proportion of 0.005 for reflected primaries is assumed. Only the relative proportions of reflected primaries to incident primaries for different surfaces are known, not the absolute proportion of reflected primary electrons to primary electrons.)

Figure 3.—Typical collector design with reflected-primary-electron beam trajectories included.

TABLE II.—COMPUTED TWT AND MDC EFFICIENCIES

(a) Overall TWT efficiency

MDC operating condition	Calculated efficiency, percent		Experimental efficiency, percent
	Without secondaries	With secondaries	
Design voltages	45.6	39.9	35.7
Intermediate voltages	43.0	41.0	39.4
Experimentally optimized voltages	43.4	42.3	41.6
Set voltages for 8- to 15.5-GHz data	40.1	39.4	39.4

(b) Collector efficiency

MDC operating condition	Calculated efficiency, percent		Experimental efficiency, percent
	Without secondaries	With secondaries	
Design voltages	88.2	82.9	80.2
Intermediate voltages	86.0	84.1	84.3
Experimentally optimized voltages	86.4	85.4	86.2
Set voltages for 8- to 15.5-GHz data	83.2	82.4	84.1

The problem with primary-electron-beam element trajectory changes that had occasionally occurred with secondary electron calculations is not observed because of the low reflected-primary current. Backstreaming reflected primaries are shown in figure 3 for a typical calculation of reflected primary current.

Experimental Verification

Recent studies have compared experimentally measured values of TWT and MDC efficiencies with calculated values of losses due to secondary electron emission, and with values calculated ignoring secondary electron emission (refs. 6 and 7). The results are presented in table II (derived from ref. 6). (The data in tables I and II are for different tubes.)

Results

In performing these calculations, it has been found that true secondary electrons cause most of the flow of current from the more depressed collector stages to the less depressed collector stages, while reflected primaries are a major cause of backstreaming into the RF interaction structure. In some cases true secondaries thought to be suppressed were not. Consequently, collector designs had to be modified by changing some of the electrode voltages, or by modifying the shape of the collector surfaces, or both. However, except in the case of the most depressed stage, proper design can suppress the true secondary electron current. Backstreaming can be reduced by using materials with relatively low reflected-primary-electron coefficients, such as graphite, or by texturing the electrode surface, or by using both methods.

Concluding Remarks

Computer programs have been developed for determining the effects of true secondary electron emission and reflected primary electrons on the performance of multistage depressed collector designs. With a small amount of additional computation, weaknesses in MDC designs can be found and corrected, and, thereby, a more accurate prediction of MDC performance can be obtained. With these programs, it has been found that most true secondaries can be suppressed by proper design, and that reflected primaries are the cause of most backstreaming from the collector to the RF interaction structure. The methods used in this study will also be useful in the design of MDC's for other O-type electron beam devices, such as klystrons.

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Cleveland, Ohio, September 3, 1986

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