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UP-DATE OF TRAVELING WAVE TUBE IMPROVEMENTS

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ABSTRACT

This paper is a brief survey of areas of progress on traveling wave tube designs, with emphasis on recent work by NASA Lewis Research Center. Data demonstrates the effect of multistage depressed collectors, the design of which is made possible by powerful NASA computer programs. Other topics include beam refocusing, rf circuit losses, and cathode testing.

INTRODUCTION

Because of the importance of traveling wave tubes (TWTs) for space communications, NASA Lewis Research Center has for several years investigated the physics of electron beam devices. Much of the technology is directly applicable to the TWTs used in electronic warfare systems. There exist agreements between NASA, the Air Force, and the Navy to cooperate in the transfer of NASA-developed technology to the TWT industry. This paper is a brief survey of recent NASA activities which could benefit the electronic warfare community.

THE SIGNIFICANCE OF TWTs

Figure 1 depicts the prime power budget of a typical electronic warfare subsystem. Nearly two-thirds of the power is consumed by the power amplifier which, typically, is a traveling wave tube. Of the power consumed by the amplifier, perhaps four-fifths is wasted and appears as heat which must be removed by a cooling system. If the efficiency of the TWT amplifier were doubled, the prime power requirement could be reduced by a third, and the critical thermal load would be halved.

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TWT COMPONENTS

Figure 2 is a schematic of a typical TWT, with the gun structure (greatly enlarged) on the left and the collector on the right. The gun forms an electron beam which travels from left to right and impacts on the collector. The beam is confined by a magnetic field and enclosed by a slow wave structure which forms the rf circuit of the tube. ECM tubes nearly always use a helix-structure rf circuit to obtain a wide bandwidth. At the input section of the rf circuit, the interaction between the traveling rf wave and the electron beam modulates the beam, causing the electrons to bunch. Toward the output, the bunched electrons interact with the rf wave, causing it to be amplified. The interaction converts some of the kinetic energy of the electrons to rf electromagnetic energy, and the greater the interaction, the more disorderly the electron beam becomes. The spent electron beam emerges from the output section of the helix and enters the collector with a range of velocities. In the past, collectors operated at or near ground potential, and all of the residual kinetic energy of the electrons was converted into heat.

MULTISTAGE DEPRESSED COLLECTORS

The collector shown in figure 2 is a simple two-stage depressed collector, representative of the latest production tubes. It is multistage in that it operates at two different potentials, and it is depressed in that the collector stages are negative relative to ground. The object of this arrangement is to sort the electrons into velocity groups and to recover most of their kinetic energy by letting them do work against the negative potential. This requires the two additional power supplies, E_{C1} and E_{C2} , in the lower right corner of figure 2.

The benefits of a multistage depressed collector (MDC) are shown in figure 3. It is evident that a tube with a low electronic efficiency, 0.1 or 0.2 of the beam power converted to rf, can be close to 50 percent efficient overall if most of the energy of the spent beam can be recovered and other losses are small. A good MDC can multiply tube efficiency by two or more.

Analysis of the Sterzer collector [1], figure 4, showed that because such a collector acted as a convergent electron lens, space charge blocking occurred and the collector could not be depressed very far. Depressed collectors were widely thought to be inherently limited and impractical. However, if a more sophisticated approach is used and electron trajectories are properly computed, allowing for the effects of electrostatic lenses and the space charge, it is possible to build practical collectors of greater than 80 percent efficiency. One

such collector has been operating for 2 years aboard the Communications Technology Satellite.

Table 1 demonstrates that the performance of such collectors may be predictable; in this case the computed currents agree with measurements on the experimental collector. (The collector programs are still being improved, debugged, and verified against experimental data.) As with the simple schematic collector of figure 2, two additional power supply voltages must be provided, but the pay-off is that more than 80 percent of the spent beam energy is recovered, reducing the power, and the total weight of power supplies, needed.

Figure 5 is a computer-generated depiction of electron trajectories in the collector described in table 1. The drawing is half of an axisymmetric longitudinal section. The lines which go from top to bottom are equipotential lines which show the complexity of the electrostatic lenses formed by the plates of the collector. The net effect is of a divergent lens which drives the electrons toward walls and prevents them, or secondary electrons generated by impacts on the walls, from backstreaming into the tube.

It is not true that inevitably as collector depression increases, beam interception on the helix increases. It would be more correct to say that poorly designed collectors fail to trap low energy electrons, so that, as the depression is increased, more of the electrons find their way back into the rf section of the tube, going in the wrong direction. The effect is power loss (and possible rf instability) which is often attributed to the beam being intercepted by the rf circuit.

This NASA collector design has been adapted by at least two manufacturers and is being applied to an experimental tube to be delivered to the Air Force. However, the design, as shown, is larger and more complex than it need be. Figure 6 is a more recent iteration of the collector design. It has not yet been built, but the computations indicate that it is as efficient as the former collector, easier to make, and less than 0.03 meter (about an inch) in diameter. Note that most of the electrons impact on the walls, so that the path for heat conduction can be short.

The NASA collectors are preceded by a short refocusing section between the rf circuit and the collector proper, as shown in figure 7. The effect is to expand and collimate the electron beam, so that the electron velocity vector is more nearly parallel to the collector axis. The object is to make it easier to sort the electrons by energy and to reduce the number of electrons which might be reflected back into the tube.

THE NASA 3-D HELICAL COMPUTER PROGRAM

The design of an efficient collector depends upon a knowledge of the three-dimensional trajectories of the electrons as they pass from the rf output section through the diminishing fields of the refocusing section into the collector. As one cannot directly measure the velocity of individual electrons, the Power Amplifier Section at NASA Lewis turned to a computer simulation. Table 2 lists the inputs and outputs of the NASA program, which is probably the most powerful program available to the tube designer. To compute 96 electron trajectories for a typical octave-bandwidth tube requires about 30 minutes of central processing unit time on the 1140 Univac computer. The program source deck is available from NASA to bona fide users.

Table 3 indicates that the computer model does, in fact, closely approximate the behavior of an actual tube. There is need for more cases to validate the model, but there is a problem in that the precision of the computer model exceeds that of the input data in most cases. One must have accurate measurements of a particular single tube, since often the variability of supposedly identical tubes, from the same production line, is greater than the error in the model.

It is probable that the NASA program accurately models all the significant variables in tube performance. Within the near future, a priori tube design will be realizable. Instead of the present practice of building many cut-and-try experimental tubes, it should be possible to do it right the first time.

RF CIRCUIT LOSSES

As long as TWTs used inefficient collectors, the losses in the rf circuit were relatively inconspicuous. As figure 8 shows, with an efficient collector, the rf losses become significant. Some rf energy is lost in the dielectric supports of the helix; other losses are caused by the electrical resistance of the helix and of the walls of the tube. The typical tube flying today has a tungsten helix. The tube designer may have estimated the rf losses as 5 or 10 percent of the rf power output. In fact, the losses may be 25 percent. The surface of the helix, which looks well polished, probably is covered with microscopic pits and cracks which increase losses at high frequencies. As the helix gets hot, the resistance of the metal increases, so the helix gets hotter still.

Designers of more efficient tubes, unless they can find a better way to fabricate tungsten, will probably be forced to use a more conductive metal, copper. A soft copper helix cannot be run hot. It requires good conductive cooling and mechanical support. There will probably be a trend toward copper

or copper plated circuit parts brazed to support structures for thermal conductivity and mechanical strength.

The rf output coupler should not be overlooked. In a broadband tube it is very difficult to get all high-power rf signals from the end of the slow wave structure, through a vacuum-tight window, and into a wave guide without absorption or reflections. Such losses cause local heating at the output which can destroy a tube.

There is a strong incentive for tube builders to continue the trend toward periodic permanent magnet (ppm) focusing of the beam. The "easy way" is to use a solenoid, but solenoids are big and heavy. They use power, perhaps a kilowatt, and generate heat which must be removed. Perhaps we will see hybrid tubes with some permanent magnets and a smaller solenoid. Computer-aided design will help to achieve better control of the beam and thus to minimize interception of the beam by the rf circuit.

CATHODES AND GUNS

The gun which forms the electron beam is clearly a critical component. NASA is investigating the physics of guns, particularly the mechanism of cathode emission. Table 4 reports the status, in 1977, of a long-term study of cathode life. Some conclusions are summarized in table 5. Note that the cold emission cathode, which is being investigated for NASA by Stanford Research Institute, offers significantly higher current density.

A cold cathode is pictured in figure 9. Conventional cathodes fail when the emissive surface is depleted or poisoned. In theory, the cold cathode might last forever. In practice, it fails by catastrophic accident, when there is arcing between the points and the gate film. Arcing can occur if there is a gas near the cathode or if there are excessive transient currents during pulsed operation. If cold cathodes are employed in tubes, the gun will be entirely redesigned.

CONCLUDING REMARKS

The Power Amplifier Section at NASA Lewis Research Center has several projects which should benefit the tube industry in general and the electronic warfare community in particular. NASA is investigating the basic physics of guns and collectors and is perfecting a computer model of the interaction between the electron beam and the rf circuit. These studies may be very useful to tube industry designers as they push traveling wave tube efficiencies toward

50 percent. Military program managers, too, should monitor these developments and appreciate the gains in system performance which can be realized by cooperative efforts to disseminate new techniques.

REFERENCE

1. Sterzer, F.: Improvement of Traveling-Wave-Tube Efficiency through Collector Potential Depression. IRE Electron Devices. ED5, no. 4, Oct. 1958, pp. 300-305.

TABLE 1. - GUNS AND BEAMS EXPERIMENTAL AND ANALYTICAL* MDS PERFORMANCE COMPARISON (AT SATURATION NEAR MID-BAND WITH 2-STAGE COLLECTOR)

	COLLECTOR VOLTAGE, V	MEASURED COLLECTOR CURRENT, mA	COMPUTED COLLECTOR CURRENT, mA
COLL (1)	0	26	27
COLL (2)	5230	73	80
COLL (3)	5230	149	134
COLL (4)	8680	13	13
COLL (5)	8690	158	154
COLL (6)	9440	14	20
		MEASURED	COMPUTED
COLLECTOR EFFICIENCY		82.1%	83.2%
POWER DISSIPATED IN COLLECTOR		595 W	630 W

*INITIAL CONDITIONS DERIVED FROM TWT AND REFOCUSING SYSTEM TRAJECTORY CALCULATIONS.

TABLE 2. - NASA LeRC 3-D HELICAL COMPUTER PROGRAM.

INPUTS:

BEAM RADIUS, CURRENT, VOLTAGE AT ENTRANCE TO HELIX
MAGNETIC FIELD DATA, SOLENOID OR PPM
CAN BE UP TO FOUR COSINE TERMS FOR EACH SECTION OF RF CIRCUIT
DIMENSIONS OF HELIX STRUCTURES, INCLUDING TAPERS AND UP TO THREE SEVERS
IMPEDANCE, PHASE VELOCITY, AND LOSSES IN dB PER INCH FOR EACH SECTION

OUTPUTS:

RF POWER, GAIN
CIRCUIT LOSSES
INTERCEPTION, AS PERCENT OF CURRENT, PERCENT OF POWER
AXIAL, RADIAL, AND ANGULAR VELOCITY COMPONENTS FOR 32 OR 96 CENTROIDS
OF CHARGE
BACKWARD WAVES ARE TREATED AS PERTURBATIONS
HARMONIC POWER CAN BE ADDED

TABLE 3.

BASIC TWT PARAMETERS	LeRC 3-D HELICAL PROGRAM MAGNETIC PROFILE PROGRAMMED	U. S. NAVY CRANE MEASURED PERFORMANCE
MAGNETIC FIELD	AT LOW EDGE	2.5 GHz
CATHODE FLUX		
IMPEDANCE	GAIN	27.2 dB
PHASE VELOCITY		27.3 dB
GEOMETRY OF TUBE	POUT	1700 W
LOSS		1715 W
VOLTAGE	INTERCEPTION	0
CURRENT		20 mA = 1.5%
HELIX DATA, PITCH, RADIUS	AT MIDBAND	3.25 GHz
POWER INPUT		
ATTENUATOR DATA	GAIN	28.1 dB
CATHODE GEOMETRY	POUT	2 048 W
	INTERCEPTION	0
		28.0
		2 000 W
		1.1%

TABLE 4. - LONG LIFE HIGH CURRENT DENSITY CATHODES
CONTRACT NAS3-14385 WITH WATKINS-JOHNSON
(STARTED 6/29/71)

OBJECTIVE: TO COMPETITIVELY EVALUATE THE PERFORMANCE OF THREE CATHODE TYPES BY ENDURANCE TESTING.

APPROACH: 1. DESIGN GUN AND TUBE FOR 2 AMPS/CM² CATHODE CURRENT OPERATION.
2. DESIGN TEST RIGS FOR AUTOMATED LIFE TEST.
3. EXPERIMENTALLY EVALUATE PERFORMANCE AS A FUNCTION OF LIFE FOR 4 CATHODE TYPES SHOWN BELOW:

CATHODE TYPE	CURRENT DENSITY	OPERATING TEMPERATURE	LIFE RESULTS
PHILIP'S IMPREGNATED	2 A/cm ²	1100° C	25 000
SEMICON DISPENSER	2 A/cm ²	1050° C	23 000 TERMINATED
G.E.: TUNGSTATE	2 A/cm ²	925° C	5 000 TERMINATED
M-CATHODES	2 A/cm ²	1100° C	15 000

TABLE 5. - CATHODES - TRADE-OFF.

TYPE	CURRENT DENSITY	TEMPERATURE	EXP. LIFE
OXIDE	0.200 A/cm ²	800° C	50 000 hr
PHILIPS "B"	2 A/cm ²	1100° C	30 000 hr
PHILIPS "M"	2 A/cm ²	1000° C	50 000 hr
PHILIPS "M"	0.5 A/cm ²	900° C	100 000 hr
COLD EM. CATH.	10 A/cm ²	20° C	?

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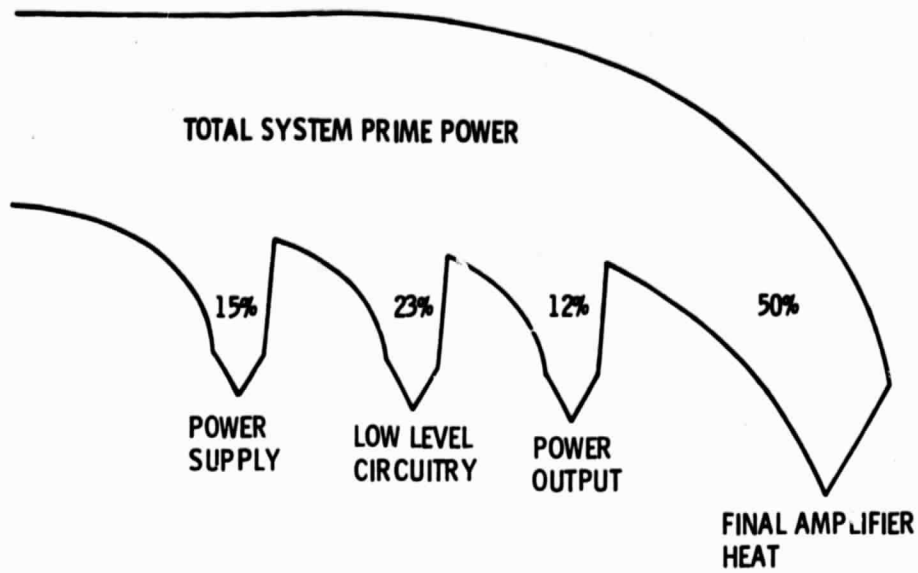


Figure 1. - ECM system. Prime power budget.

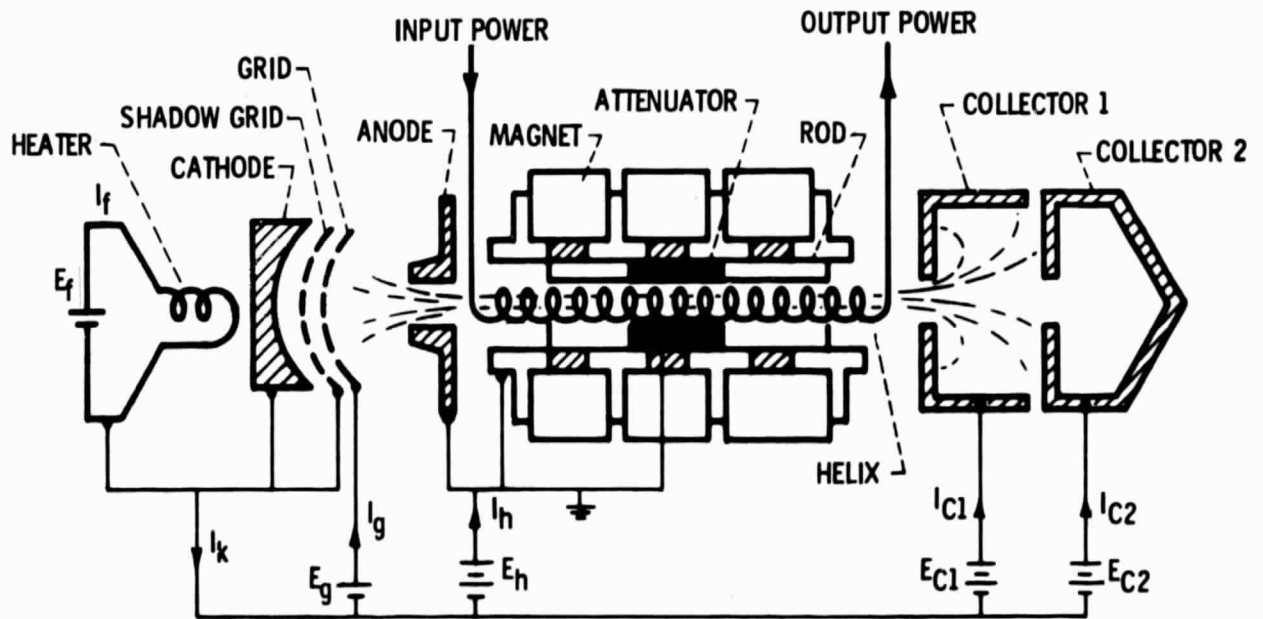


Figure 2. - Schematic of TWT and power supplies.

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FOR $\eta_{CT} < 1$

$$\eta_o = \frac{\eta_{CT} \cdot \eta_e}{1 - \eta_c + \eta_e \eta_c}$$

η_e - ELECTRONIC
 η_c - COLLECTOR
 η_{CT} - CIRCUIT
 η_o - OVERALL

EFFICIENCY

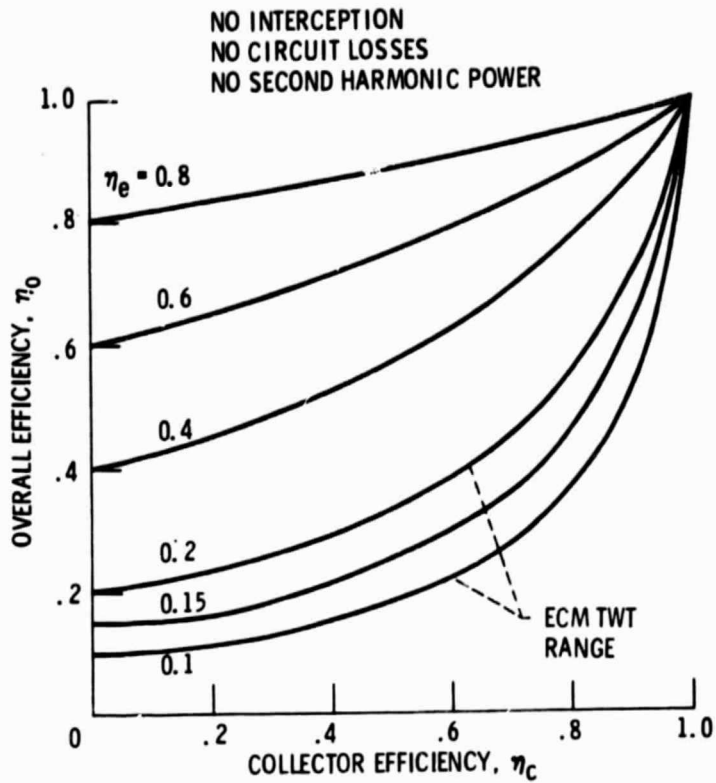


Figure 3. - Overall efficiency vs. collector efficiency.

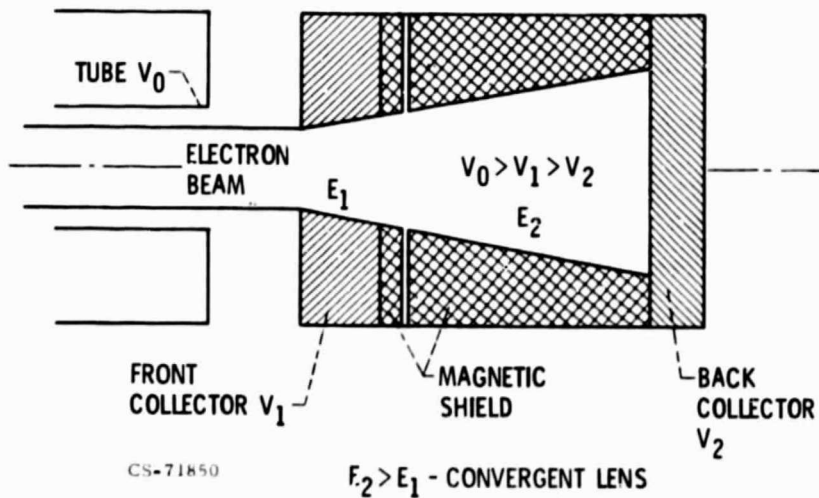


Figure 4. - Sterzer (RCA) collector.

GUNS AND BEAMS

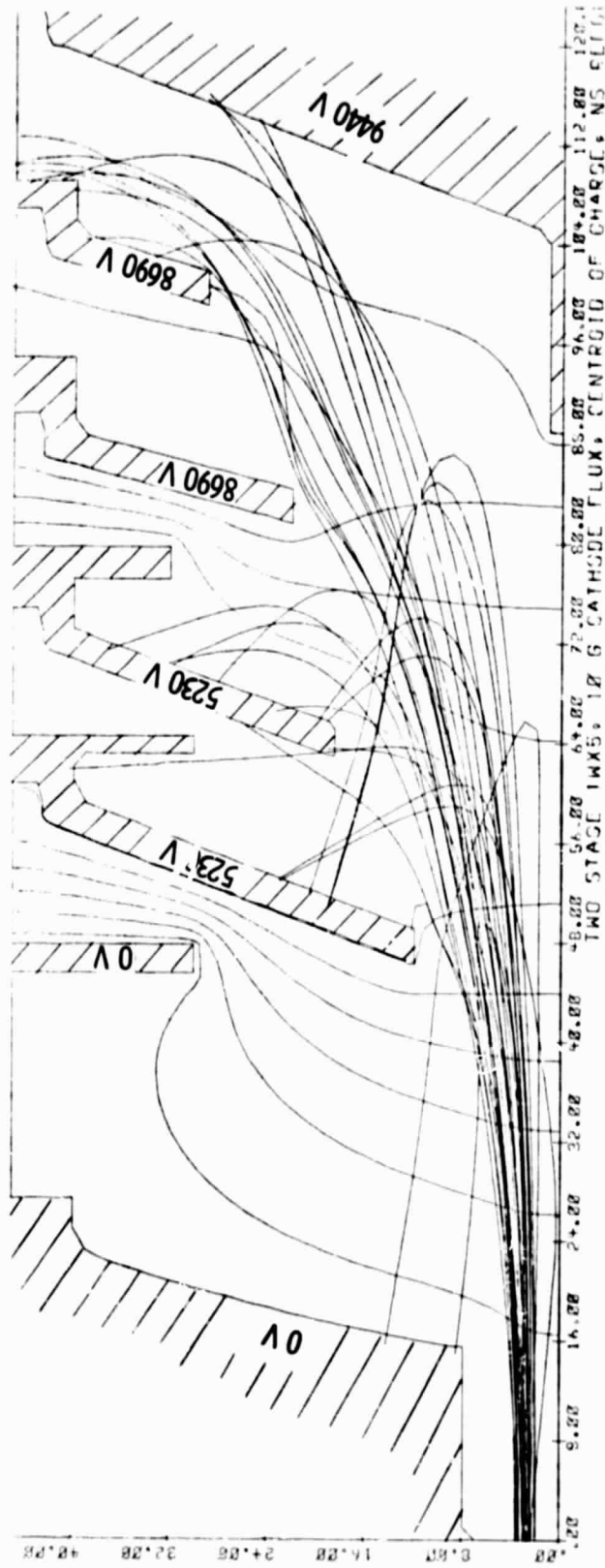


Figure 5. - Electron trajectories in experimental collector.

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GUNS AND BEAMS

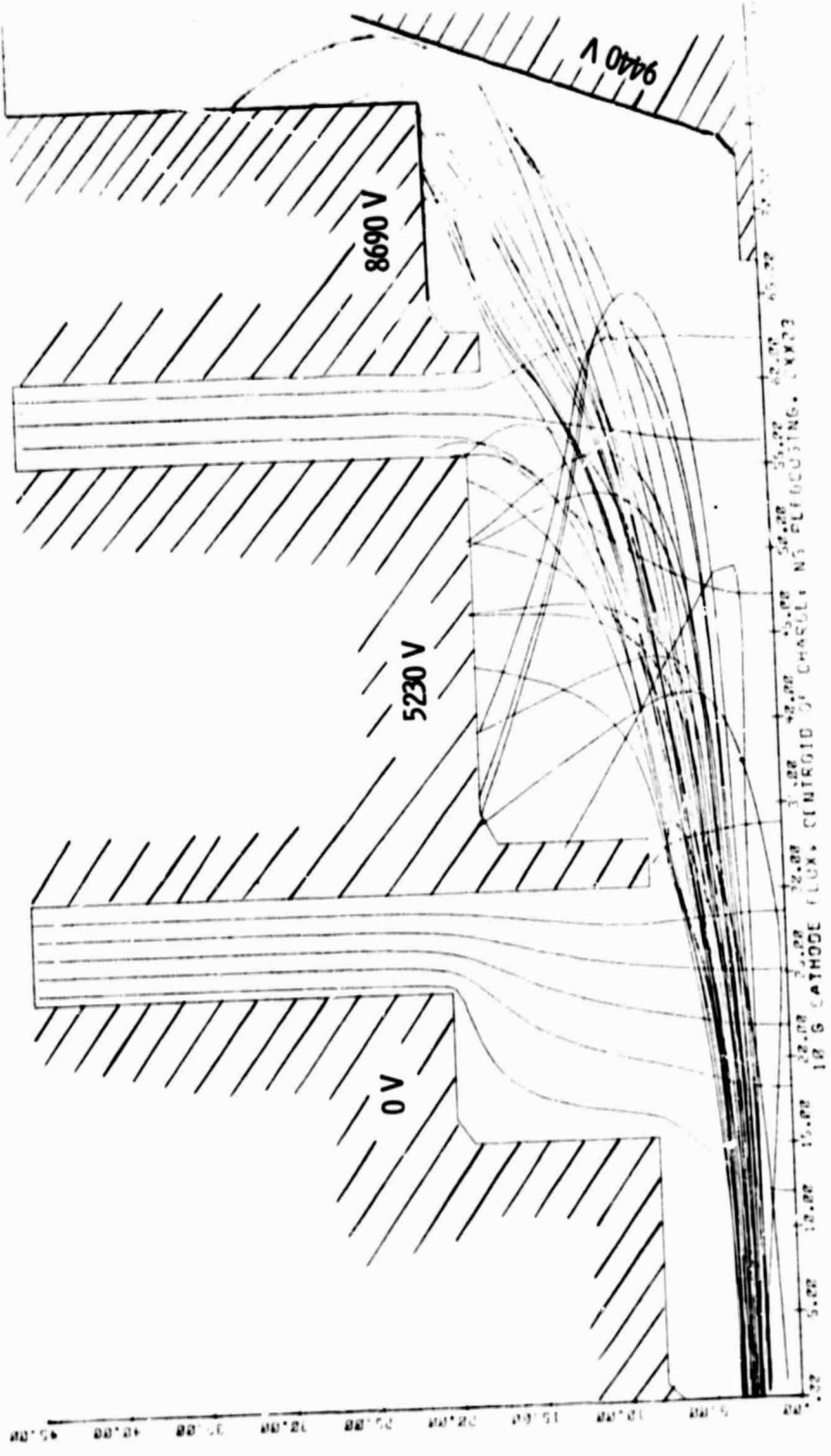


Figure 6. - Improved collector design.

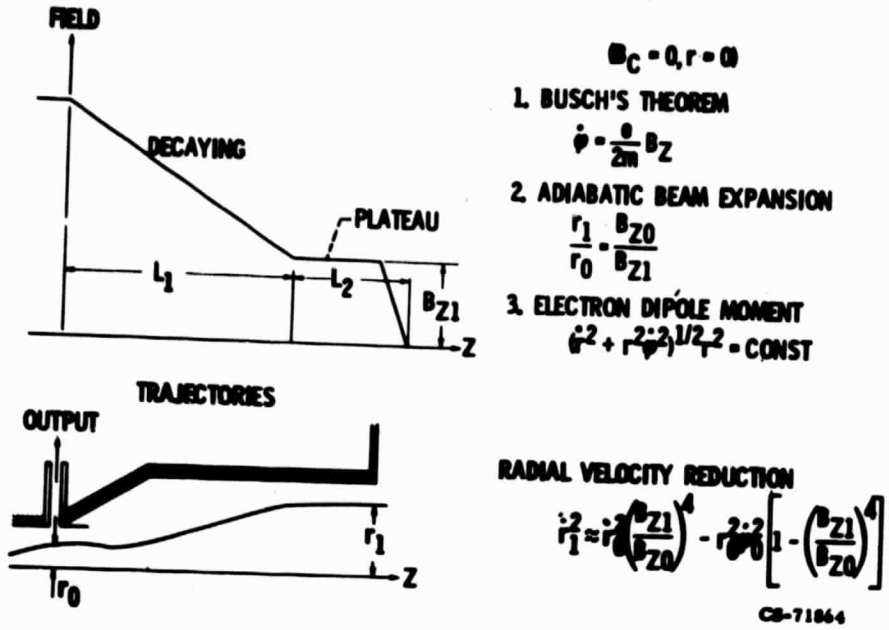
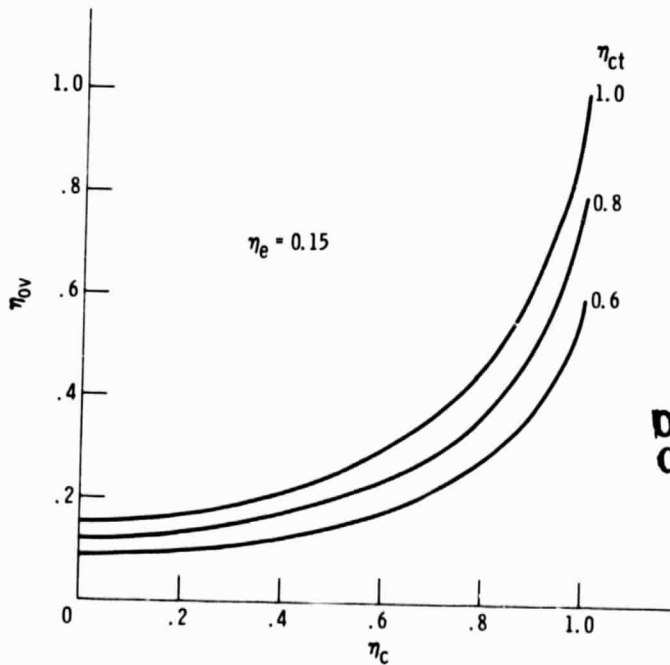


Figure 7. - Schematic of refocusing system.



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Figure 8. - Effect of circuit losses on the overall tube efficiency for $\eta_e = 0.15$.

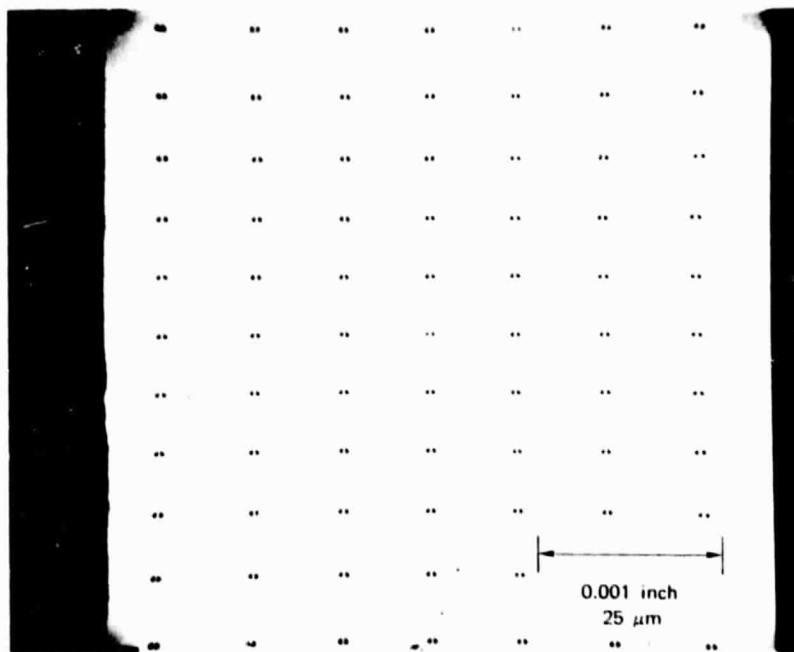


Figure 9. - Field emission cathode.

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