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SUMMARY

An axisymmetric, multistage depressed collector of fixed geometric design was evaluated in conjunction with an octave-bandwidth, dual-mode traveling wave tube (TWT). The TWT was operated over a wide range of conditions to simulate different applications. The collector was operated in three-, four-, and five-stage configurations, and its performance was optimized (within the constraint of fixed geometric design) over the range of TWT operating conditions covered.

For operation of the dual-mode TWT at and near saturation, the collectors increased the TWT overall efficiency by a factor of $2\frac{1}{2}$ to $3\frac{1}{2}$. Collector performance was relatively constant for both the high and low TWT modes and for operation of the TWT across an octave bandwidth.

For operation of the TWT in the linear, low-distortion range, collector efficiencies of 90 percent and greater were obtained, leading to a five- to twelvefold increase in the TWT overall efficiency for the range of operating conditions covered and reasonably high (>25 percent) overall efficiencies well below saturation. With collectors of this efficiency it becomes practical to design dual-mode TWT's such that the low mode can represent operation well below saturation. Consequently, the required pulse-up in beam current can be reduced and this mitigates beam control and dual-mode TWT circuit design problems.

The improvements in the TWT overall efficiency were somewhat limited (especially at low TWT electronic efficiencies) by excessive beam interception in this particular TWT sample.

INTRODUCTION

If the residual energy in the spent electron beam that exits from a microwave tube could be efficiently recovered, substantially less prime power would be required to operate the tube and the heat dissipation problem would be mitigated. In a joint USAF-NASA program, the Lewis Research Center is attempting to improve the efficiency of traveling wave tubes (TWT's) for use in electronic countermeasure systems by applying multistage-depressed-collector (MDC) and spent-beam-refocusing techniques developed at Lewis (refs. 1 to 4). The refocusing system and MDC designs are produced by combining analyses of the TWT, the refocusing system, and the MDC (ref. 5). Electrons are tracked from the radiofrequency (rf) input in the TWT to their collection on the MDC electrodes. The experimental program stresses accurate and complete evaluation of TWT and MDC performance. The MDC efficiencies are determined from measured quantities without any assumptions, and a final system energy balance is obtained.

Previous work (refs. 2 and 6) with an octave-bandwidth, periodic-permanent-magnet (PPM)-focused, high-performance TWT stressed MDC performance optimization for TWT operation at and near saturation. The TWT-MDC performance was then evaluated (at this fixed set of collector operating conditions) across the octave bandwidth at and below saturation. Collector efficiencies in excess of 80 percent (at saturation) were demonstrated across an octave bandwidth, and collector performance (both at and below saturation) was relatively insensitive to the operating frequency. These results were obtained with a single, rather complex MDC geometric design consisting of six electrodes (fig. 1), including electrodes at ground and cathode potentials.

There are, however, circumstances (applications) where different types of collector optimization must be stressed, for example,

(1) Where a dual-mode TWT is pulsed (at and/or near saturation) between the low and pulsed-up (high) modes

(2) Where a large (10:1) pulse-up capability in the output power is needed and the low mode represents TWT operation well below saturation

(3) Where the TWT must be operated at constant output power in the linear, low-distortion range (typically, 4 dB or more below saturation) and consequently at very low electronic efficiencies (e.g., 2 to 4 percent for the application discussed in ref. 7)

(4) Where the electron beam in the TWT must be "on" at all times but the TWT is in a standby mode (no rf input) most of the time

To evaluate the MDC performance for these particular applications, the same MDC and refocusing system were added to an octave-bandwidth, PPM-focused, dual-mode TWT with the capability of a 2:1 pulse-up in output power. The collector performance was individually optimized (within the constraint of fixed collector geometric design) for each of these applications. The MDC sensitivity to the operating frequency across an octave bandwidth was evaluated for saturated operation of the TWT (the most difficult case because of large changes in rf output power). The results of these tests are reported herein.

SYMBOLS[1]

I_B	true interception current in forward direction
I_{body}	$I_B + I_S$

[1] See, also, figures 2 and 3.

I_{e1}	backstreaming current to undepressed collector electrode
I_k	cathode current or beam current
I_S	backstreaming current to TWT body
P_{body}	(Total rf losses in TWT) + (True beam interception losses)
P'_{body}	P_{body} + (All or part of backstreaming power)
P_{coll}	total power in spent beam that enters MDC
P_{fund}	rf output assoicated with fundamental frequency
P_{hrm}	rf output resulting from harmonic frequencies
P_{rf}	total rf output ($P_{fund} + P_{hrm}$)
V_k	cathode potential (always negative for work reported herein)
$\overline{V}$	average potential of intercepted electrons

EXPERIMENTAL EVALUATION OF TWT AND MDC PERFORMANCE

To completely and accurately evaluate TWT and MDC performance, it is necessary to determine the final power distribution in the system. This distribution is shown in figure 2 in the form of power flow and electron flow diagrams for a TWT with a depressed collector. Part of the initial beam power I_kV_k appears as measured rf output power at the fundamental and (possibly) harmonic frequencies, and part is dissipated on the TWT body as the sum of the rf losses in the TWT and the intercepted beam power in the forward direction. The rest enters the collector. Part of this kinetic power is recovered as useful electric power, and part is dissipated as thermal power on the collector plates. Collector efficiency is defined as $P_{recovered}/P_{coll}$.

With a depressed collector, backstreaming electrons (I_S and I_{e1} in fig. 2(b)) can return significant power to the TWT body. Since any backstreaming produced by the depressed collector must be charged against its efficiency, this backstreaming power must be evaluated or exaggerated collector efficiencies will result (e. g., ref. 8).

Neither P_{coll}, P_{body}, nor true beam interception I_B can be measured directly in the presence of an MDC. Without these measured values the determination of MDC efficiencies requires certain assumptions that can significantly affect the computed collector performance:

(1) Assumption of the circuit losses

(2) Assumption of the true intercepted current in the forward direction

(3) Assumption of the average energy of the intercepted electrons

With these assumptions, P_{coll} can be computed from the equation

$$P_{coll} = V_k I_k - P_{rf} - \text{(Circuit losses)} - (I_B \overline{V})$$

as shown in figure 2.

However, it has been our experience at Lewis that both the circuit losses and the true beam interception can vary widely, even between TWT's of identical design (ref. 6). Circuit losses (at a given frequency) can be strongly affected by reflections due to mismatches (individual TWT imperfections); and the TWT's are usually focused to meet system specifications, not to produce minimum beam-current interception.

The need for making any assumptions can be avoided entirely only by first operating the same TWT with a suitable thermally isolated undepressed collector. The power returned to the TWT body by backstreaming electrons (secondaries) from such a collector is negligible. The power flow diagram for a TWT with an undepressed collector is shown in figure 3. The power into the collector P_{coll} can be measured directly. Alternatively, the rf output power P_{rf} and the total body power P_{body} can be thermally measured, and P_{coll} can be computed from measured quantities. Since only the total body power is needed to compute P_{coll}, with this experimental approach the questions of circuit efficiency, true interception, and average energy of the intercepted electrons are irrelevant.

EXPERIMENTAL TWT

The Teledyne MEC TWT model MTZ 7000, serial number 102, as modified for use in this program, and its performance characteristics are shown in figure 4. A refocusing system consisting of two coils was added, and the TWT was mounted on a 25.4-centimeter- (10-in.-) diameter ultra-high-vacuum (UHV) flange. The UHV valve shown (ref. 9) was designed to keep the TWT under vacuum during MDC installation and changes and thus to facilitate startup and minimize cathode activation problems.

This TWT, as delivered, had an undepressed, thermally isolated, water-cooled collector mounted on a matching 25.4-centimeter- (10-in.-) diameter vacuum flange. This special collector was required for the bench test.

EXPERIMENTAL PROGRAM

BENCH TEST

The bench test was conducted to document the performance of the TWT with an undepressed spent-beam collector so that TWT performance changes, if any, due to the MDC could be determined and so that accurate MDC efficiency measurements could later be made. The rf load, the TWT body, and the collector were all thermally isolated and water cooled. Thermal power to each was measured by a combination of flowmeter and thermopile. Since the collector was undepressed, the power returned to the TWT by any backstreaming electrons was negligible. The measured P_{body} was, therefore, the sum of the total rf losses in the TWT and the interception losses.

MULTISTAGE-DEPRESSED-COLLECTOR TEST

In the MDC test setup (fig. 5) the TWT was mounted on a matching flange on a UHV system. The MDC was mounted directly on the UHV flange, which housed the TWT and the vacuum valve. Each MDC electrode, including the undepressed electrode, was thermally and electrically isolated and water cooled. The spent-beam power recovered by each MDC electrode, as well as the thermal (kinetic) power dissipated on each electrode, was measured. A vacuum feedthrough drove a variable-length spike. Over its range of variability, the length of the spike significantly affected the electric field distribution within the collector, and its optimum length could be established quickly and easily for each MDC configuration. Since the refocusing coils and polepieces were outside the vacuum, they could be manipulated and moved over their designed range of variability while the TWT was operating. Together with variation of the refocusing coil currents, this enabled the rapid optimization, within limits, of the refocusing field profile. Once established, this profile could be synthesized with a permanent-magnet refocusing system.

A typical experimental collector is shown in figure 5. This fully demountable mechanical design was chosen for experimental convenience. Separate water cooling (and calorimetry) of each collector electrode was chosen for diagnostic purposes and for its ability to provide information for the eventual thermal design of a conduction-cooled MDC. The internal (active) volume of the MDC is that within the inner diameter of the cooling lines (5.1 cm). The electrode geometries within this volume are critical to the MDC performance, but the passive electrode support structure outside is not. Extensive thermal and mechanical design changes must be made to adapt these MDC's to practical TWT's.

A novel data acquisition system was used to optimize collector efficiency under various conditions. This system provided an analog real-time readout of the recovered power as any of the system variables were changed while the TWT was operating. These variables were the individual collector stage voltages, the refocusing coil currents, the polepiece locations, and the spike length.

Maximizing the recovered power was identical to maximizing the MDC efficiency. Once the optimum combination of operating conditions was found, an automated data acquisition system was used for actual data taking.

EXPERIMENTAL RESULTS

RESULTS OF BENCH TEST

The dual-mode TWT was operated at saturation across the octave bandwidth in both the low and high modes. At selected operating frequencies the TWT performance and fixed TWT losses were evaluated as far as 12 decibels below saturated output power. Bench test data were obtained at 10 percent duty cycle in the high mode and at 20 percent in the low mode (instead of continuous-wave operation) for the following reasons:

(1) TWT 102 exhibited a relatively poor cold output match over much of the lower half of the band and at the high band-edge.

(2) In previous tests with identical undepressed, spent-beam collectors (refs. 2 and 6), extreme heating of parts of the collector led to migration of copper to the TWT output section.

The rf output power at the fundamental frequency, the TWT body losses (sum of rf losses and interception losses), and the total fixed TWT losses (sum of TWT body losses and harmonic power generated) are shown as a function of frequency in figures 6 and 7 for the low and high modes, respectively. It is evident that the fixed TWT losses at some frequencies were extremely large; at the low band-edge they substantially exceeded the useful rf output power. This was due to the combination of very low effective circuit efficiencies (caused by mismatches) at some frequencies and the relatively high beam-current interception (2.8 percent for the direct-current beam). The rf output power was correspondingly low where the rf circuit losses were very large.

After the bench test was completed, the UHV valve (fig. 4) was closed and the undepressed, spent-beam collector was removed. The TWT was kept under a hard vacuum during the subsequent MDC installation, and no processing (gradual outgassing) of the TWT was required.

RESULTS OF MULTISTAGE-DEPRESSED-COLLECTOR TESTS

The collector shown in figure 1 was added to the TWT, and the combination was evaluated. The MDC was operated in three-, four-, and five-stage configurations. The number of MDC stages is defined as the number of distinct voltages (other than ground potential) needed to operate the MDC. In the three-stage configuration, electrodes 2 and 3 and electrodes 4 and 5 were electrically connected (fig. 1). In the four-stage configuration, electrodes 2 and 3 were electrically connected. In all the configurations, the most depressed stage (electrode 6 in fig. 1) was always operated at cathode potential.

The single MDC geometric design used in these tests had been experimentally optimized for a continuous-wave TWT (Teledyne MEC 5897C) operating at an electronic efficiency of 17 percent. Within this constraint of fixed geometry (not optimum for this dual-mode TWT or for a broad range of operating conditions), the MDC performance was optimized (for the various operating conditions) by varying

(1) The electrode voltages
(2) The refocusing system profile
(3) The MDC spike length

Data for the low and pulsed-up (high) modes were obtained at duty cycles of 100 and 10 percent, respectively, unless stated otherwise.

Dual-Mode TWT-MDC Performance at and near Saturation

To evaluate the MDC performance (at a fixed set of operating conditions) when the TWT was pulsed between the pulsed-up and low modes, collector performance was individually optimized at each of the following operating points (at 8.4 GHz):

(1) Saturated output in the low mode
(2) Saturated output in the pulsed-up mode
(3) Rated power (P_{rf} = 400 W) in the low mode
(4) Rated power (P_{rf} = 800 W) in the pulsed-up mode

The TWT-MDC performance in both the high and low modes was then evaluated for each of this set of fixed MDC operating conditions. The results are shown in tables I to III for the three-, four-, and five-stage collectors, respectively.

A very significant improvement in the TWT overall efficiency (by a factor of $2\frac{1}{2}$ to $3\frac{1}{2}$ for the range of conditions covered) was obtained with each of the MDC's. Comparing the results as a function of the number of collector stages showed

(1) That the four-stage collector was significantly more efficient than the three-stage collector (by about 4 percentage points)
(2) That only a small further improvement in collector efficiency (< 1 percentage point) was obtained with the five-stage collector

The collector performance was relatively constant between the pulsed-up and continuous-wave modes (particularly when the collector was optimized for the pulsed-up mode) in spite of a 2-to-1 change in the output power and a 28 percent change in the beam perveance.

Continuous-wave (cw) operation of the TWT in the low mode produced considerably more heating of the rf circuit than low-mode operation at a duty cycle of 20 percent, especially at and near saturation. At saturation the rf output power at cw was down by about 50 watts, and the body power was up by approximately this amount over that of the

TWT-MDC operating at a duty cycle of 20 percent. The measured rf output power at a duty cycle of 20 percent agreed very closely with the bench-test results.

The additional heating was taken into account in computing the collector efficiencies for tables I to III. Although collector performance was virtually identical at the 20- and 100-percent duty cycles, the overall efficiencies were substantially different. For example, with a four-stage collector, overall efficiencies at saturation of 38.3 and 43.5 percent were obtained at duty cycles of 100 and 20 percent, respectively.

To evaluate MDC performance for octave-bandwidth operation of the dual-mode TWT, saturated operation in the pulsed-up mode (the most difficult case for the collector) was selected. The MDC performance (for both four- and five-stage collectors) was optimized at the operating frequency (8.4 GHz) that produced the maximum output power. The TWT-MDC performance (at this fixed set of collector operating conditions) was then evaluated across the octave bandwidth.

Previous work (ref. 6) demonstrated that the MDC performance was relatively constant for TWT operation across an octave bandwidth (even with large changes in the output power). For example, the total range of five-stage-collector efficiencies was 2.6 percentage points at saturation and 1.9 percentage points for TWT operation at rated power across the octave bandwidth. Similarly, for the work reported herein, collector efficiencies of 81.2 to 83.0 percent and 81.8 to 83.2 percent were obtained with the four- and five-stage collectors, respectively.

The overall TWT performance is shown in figure 8. The TWT overall efficiency exceeded 40 percent over a substantial part of the octave bandwidth in spite of very substantial fixed TWT losses (fig. 7).

Dual-Mode TWT-MDC Performance for 10:1 Pulse-Up in Output Power

For certain applications, both in electronic countermeasures and communications (ref. 7), a large (up to 10:1) pulse-up capability in output power is required. The approach commonly used to achieve this is to pulse up the beam current. Typically, beam-current pulse-up ratios (over the low mode) of 3 to 5 have been considered for a 10:1 pulse-up in output power. However, this introduces some severe problems in beam optics and control (especially for PPM-focused TWT's) and in TWT circuit design (a number of important TWT parameters are functions of the beam current and the effective beam radius).

The required pulse-up in beam current can be significantly reduced (and the associated problems mitigated) if the low mode can be accomplished by operation of the TWT well below saturation. This alternative approach is practical only if an extremely efficient (in the range of 90 percent) depressed collector for this low mode can be used to ensure a reasonable TWT overall efficiency. The problem of developing such a collector, however, is compounded by the fact that the collector operation cannot be optimized for the low mode since extreme collector depression for the low mode (low power well below saturation) can produce a disastrous amount of backstreaming to the TWT in the pulsed-up mode and subsequent TWT failure. Therefore, MDC optimization involves a compromise between the two operating modes.

To evaluate the effectiveness of this type of MDC (for a fixed set of operating conditions) over a 10:1 pulse-up range, where the high mode represents saturated operation (the most difficult case), the TWT was operated at output powers from 86 to 865 watts. The results for the three-, four-, and five-stage collectors are shown in tables IV, V, and VI, respectively. The compromise, which favored the low mode, resulted in maximum overall efficiency losses of 2.6 percent in the low mode and 8.1 percent in the high mode. For this wide range of TWT operating conditions, each additional depressed stage (four as opposed to three and five as opposed to four) produced a significant increase in both the collector and TWT overall efficiencies. The relatively high direct-current beam interception of 2.8 percent significantly limited the overall efficiency attainable for the larger pulse-up ratios. (For the 9:1 ratios in tables IV to VI the intercepted beam power was approximately equal to the rf power.)

A 10:1 pulse-up in output power was emphasized in these tests. For smaller pulse-up ratios and (in particular) where the high mode also represented operation below saturation (e.g., ref. 7) significantly higher collector and overall efficiencies should be possible (through individual optimization for each case) than those shown in tables IV to VI.

For the range of MDC and TWT overall efficiencies represented by the linear range of the low mode, small improvements in MDC efficiency can lead to substantial improvements in overall efficiency (e.g., fig. 3 of ref. 2). Therefore, with a fully optimized MDC design for a given application, it should be possible to achieve the 90 percent and greater collector efficiencies required to use this alternative approach to designing dual-mode TWT's.

The collector efficiencies for the direct-current (unmodulated) beam, for these fixed sets of MDC operating conditions, are also shown in tables IV to VI. The 91 to 94 percent collector efficiencies are indicative of those obtainable when the direct-current beam must be "on" at all times and the TWT (when modulated) operated at saturation. Where the TWT (when modulated) operated at 4 decibels below saturation, collector efficiencies of 94.1, 94.6, and 95.1 percent were obtained with a direct-current beam for the three-, four-, and five-stage collectors, respectively, with little, if any reduction in optimum collector performance for the modulated beam.

TWT-MDC Performance for Operation of TWT in Linear Range

The TWT was operated over its linear range in the low and pulsed-up modes to simulate applications where the TWT must be operated at constant power in the linear, low-distortion range and consequently at very low electronic efficiencies (e.g., 2 to 4 percent for the application discussed in ref. 7). The MDC performance was individually optimized at each TWT operating point.

The results for the low mode are shown in tables VII, VIII, and IX for the three-, four-, and five-stage collectors, respectively. The collector and TWT overall efficiencies obtained with the three MDC's are compared in figures 9 and 10, respectively. Each collector produced a very dramatic improvement in the overall efficiency: from a factor of 5 to 11 for the three-stage collector to a factor of 6 to $12\frac{1}{2}$ for the five-stage collector, over the range of operating conditions covered. The five-stage-collector efficiencies exceeded 90 percent over the entire range. Figures 9 and 10 show that improvement obtained from additional stages (four as opposed to three and five as opposed to four) decreased for operation increasingly below saturation. For these collectors, the reason is that at very low levels of electronic efficiency most of the spent beam was collected on the upper electrodes (4 and 5 in fig. 1) and that the optimum (five stage) voltages of these electrodes differed by only a few hundred volts.

The results for the pulsed-up mode are shown in tables X and XI. At a given level below saturation the overall efficiencies for the pulsed-up mode were significantly higher than those for the low mode because of the higher electronic efficiency of the TWT in the pulsed-up mode. At a given electronic efficiency the collector and TWT overall efficiencies were slightly lower, possibly because of the higher beam perveance in the pulsed-up mode (e.g., fig. 4 of ref. 5).

The relatively large intercepted beam power (equal to the rf output power at electronic efficiencies of 2.8 and 2.1 percent for the low and pulsed-up modes, respectively) significantly limited the overall efficiencies attainable. With a fully optimized MDC design (e.g., optimized geometric design) and minimized beam interception losses, it should be possible to obtain relatively high (25 percent or more) overall efficiencies for TWT operation well below saturation.

CONCLUDING REMARKS

An axisymmetric, depressed collector of fixed geometric design was optimized and evaluated over a wide range of traveling-wave-tube (TWT) and multistage-depressed-collector (MDC) operating conditions. The combination of refocusing system and MDC proved to be highly adaptable to a wide variety of TWT applications (operating conditions).

For operation of the dual-mode TWT near saturation, the MDC's improved the TWT overall efficiency by a factor of $2\frac{1}{2}$ to $3\frac{1}{2}$ for the operating conditions covered. Collector performance was relatively constant for both the pulsed-up and low modes and for operation of the TWT across an octave bandwidth.

For operation of the TWT well below saturation, the 90 percent and greater MDC efficiencies led to a five- to twelvefold increase in TWT overall efficiency for the range of operating conditions. The demonstrated 90 percent collector efficiencies for the low mode of a dual-mode TWT operating over a 10:1 range in output power could have significant implications for future dual-mode TWT design.

For this range of MDC and TWT electronic efficiencies, small improvements in MDC efficiency can lead to substantial improvements in overall efficiency. Moreover, the magnitudes of the reported overall efficiencies were significantly limited by the very substantial fixed TWT losses, which were

1. Excessive interception for operation of the TWT in the linear region
2. Excessive circuit losses for operation of the TWT at and near saturation

Therefore, with TWT's designed for minimum fixed losses and with individually optimized MDC geometric designs for each specific application, substantially higher overall efficiencies than those reported can be expected.

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TABLE I. - PERFORMANCE OF DUAL-MODE TWT WITH THREE-STAGE COLLECTOR AT AND NEAR SATURATION

[Frequency, 8.4 GHz.]

Operating condition	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
Saturation[a]			
Pulsed-up mode	18.8	44.9	76.6
Low mode	11.7	35.0	80.4
Saturation:[b]			
Pulsed-up mode	18.7	46.2	78.2
Low mode	11.9	34.2	79.1
Rated power:[a, b]			
Pulsed-up mode	17.4	46.7	80.7
Low mode	11.1	35.1	81.7

[a]Optimized in low mode.
[b]Optimized in pulsed-up mode.

TABLE II. - PERFORMANCE OF DUAL-MODE TWT WITH FOUR-STAGE COLLECTOR AT AND NEAR SATURATION

[Frequency, 8.4 GHz.]

Operating condition	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
Saturation:[a]			
Pulsed-up mode	18.6	48.8	81.1
Low mode	11.8	39.0	84.5
Saturation:[b]			
Pulsed-up mode	18.6	50.2	82.5
Low mode	11.7	38.3	83.9
Rated power:[a]			
Pulsed-up mode	17.3	48.0	82.1
Low mode	11.2	38.4	84.9
Rated power:[b]			
Pulsed-up mode	17.2	48.9	83.0
Low mode	11.1	38.1	84.7

[a]Optimized in low mode.
[b]Optimized in pulsed-up mode.

TABLE III. - PERFORMANCE OF DUAL-MODE TWT WITH FIVE-STAGE COLLECTOR AT AND NEAR SATURATION

[Frequency, 8.4 GHz.]

Operating condition	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
Saturation:[a]			
Pulsed-up mode	18.8	48.9	81.0
Low mode	12.1	40.8	85.5
Saturation:[b]			
Pulsed-up mode	18.7	51.0	83.2
Low mode	12.0	39.7	84.6
Rated power:[a]			
Pulsed-up mode	17.2	47.4	81.7
Low mode	11.1	39.1	85.7
Rated power:[b]			
Pulsed-up mode	17.3	49.5	83.5
Low mode	11.2	38.2	84.7

[a]Optimized in low mode.
[b]Optimized in pulsed-up mode.

TABLE IV. - PERFORMANCE OF DUAL-MODE TWT WITH THREE-STAGE COLLECTOR FOR A FIXED SET OF MDC OPERATING CONDITIONS

[Frequency, 8.4 GHz.]

Mode	Pulse-up ratio, $\frac{P_{rf}\text{ (high mode)}}{P_{rf}\text{ (low mode)}}$	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
Pulsed up	[a]1.0	18.6	41.2	72.1
	2.0	9.2	33.9	83.2
Low	3.0	8.0	30.4	83.5
	4.0	6.0	26.2	85.1
	5.0	4.8	22.6	85.7
	6.0	4.0	20.0	86.1
	7.0	3.4	18.4	86.9
	8.0	3.0	16.4	86.8
	9.0	2.7	14.6	86.5
	10.0	2.4	13.7	87.0
	Direct-current beam	0	0	91.2

[a]At saturation.

TABLE V. - PERFORMANCE OF DUAL-MODE TWT WITH FOUR-STAGE COLLECTOR FOR A FIXED SET OF MDC OPERATING CONDITIONS

[Frequency, 8.4 GHz.]

Mode	Pulse-up ratio, $\frac{P_{rf}\text{ (high mode)}}{P_{rf}\text{ (low mode)}}$	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
Pulsed up	[a]1.0	18.7	42.1	73.0
	2.0	9.4	28.9	77.2
Low	3.0	8.1	30.7	83.6
	4.0	6.1	27.9	86.4
	5.0	4.8	25.5	88.2
	6.0	4.0	23.4	89.1
	7.0	3.5	21.0	89.2
	8.0	3.0	19.2	89.5
	9.0	2.7	17.6	89.7
	10.0	2.4	15.7	89.2
	Direct-current beam	0	0	92.4

[a]At saturation.

TABLE VI. - PERFORMANCE OF DUAL-MODE TWT WITH FIVE-STAGE MDC FOR A FIXED SET OF MDC OPERATING CONDITIONS

[Frequency, 8.4 GHz.]

Mode	Pulse-up ratio, $\frac{P_{rf}\text{ (high mode)}}{P_{rf}\text{ (low mode)}}$	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
Pulsed up	[a]1.0	18.7	43.2	74.4
	2.0	9.4	38.3	86.3
Low	3.0	8.1	34.9	87.1
	4.0	6.0	30.9	88.9
	5.0	4.9	27.3	89.3
	6.0	4.0	24.4	89.8
	7.0	3.4	22.3	90.4
	8.0	3.0	20.2	90.5
	9.0	2.7	18.9	90.7
	10.0	2.4	17.1	90.6
	Direct-current beam	0	0	93.9

[a]At saturation.

TABLE VII. - PERFORMANCE OF DUAL-MODE TWT WITH THREE-STAGE COLLECTOR FOR TWT OPERATION IN LINEAR RANGE

[Low mode; frequency, 8.4 GHz.]

Output power, level below saturation, dB	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
3.7	5.0	24.8	86.8
4.7	4.0	21.4	87.5
5.9	3.0	17.5	88.0
6.8	2.5	16.3	89.4
7.7	2.0	14.9	90.8
10.6	1.0	9.3	92.5
13.6	.5	5.6	93.6
Direct-current beam	0	0	96.2

TABLE VIII. - PERFORMANCE OF DUAL-MODE TWT

WITH FOUR-STAGE COLLECTOR FOR

TWT OPERATION IN LINEAR RANGE

[Low mode; frequency, 8.4 GHz.]

Output power level below saturation, dB	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
3.7	5.0	27.3	88.8
4.7	4.0	23.8	89.5
5.9	3.0	19.5	89.8
6.7	2.5	17.8	90.8
7.6	2.0	16.0	91.7
10.7	1.0	10.1	93.3
13.6	.5	6.0	94.3
Direct-current beam	0	0	96.3

TABLE IX. - PERFORMANCE OF DUAL-MODE TWT

WITH FIVE-STAGE COLLECTOR FOR

TWT OPERATION IN LINEAR RANGE

[Low mode; frequency, 8.4 GHz.]

Output power level below saturation, dB	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
3.6	5.1	30.2	90.5
4.6	4.1	26.2	90.9
5.9	3.0	21.0	90.9
6.8	2.5	19.2	92.0
7.6	2.0	17.3	92.5
10.7	1.0	10.3	93.6
13.7	.5	6.3	94.8
Direct-current beam	0	0	96.7

TABLE X. - PERFORMANCE OF DUAL-MODE TWT

WITH FOUR-STAGE COLLECTOR FOR

TWT OPERATION IN LINEAR RANGE

[Pulsed-up mode; duty cycle, 100 percent; frequency, 8.4 GHz.]

Output power level below saturation, dB	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
4.0	7.5	35.0	87.6
4.3	7.0	33.8	88.0
5.0	6.0	30.5	88.0
5.8	5.0	26.8	88.1
6.7	4.0	23.2	88.3
7.9	3.0	19.3	89.0
9.8	2.0	15.0	90.5
12.7	1.0	9.4	92.0
15.7	.5	5.8	93.6
Direct-current beam	0	0	95.3

TABLE XI. - PERFORMANCE OF DUAL-MODE TWT

WITH FIVE-STAGE COLLECTOR FOR

TWT OPERATION IN LINEAR RANGE

[Pulsed-up mode; duty cycle, 100 percent; frequency, 8.4 GHz.]

Output power level below saturation, dB	Overall efficiency without MDC, percent	Overall efficiency with MDC, percent	Collector efficiency, percent
4.0	7.5	35.9	88.3
4.3	7.0	34.3	88.2
5.0	6.0	31.9	89.0
5.7	5.0	28.1	88.9
6.7	4.0	23.7	88.9
8.4	3.0	19.4	89.3
9.7	2.0	16.1	91.4
12.7	1.0	9.9	92.6
15.5	.5	6.1	93.8
Direct-current beam	0	0	95.6

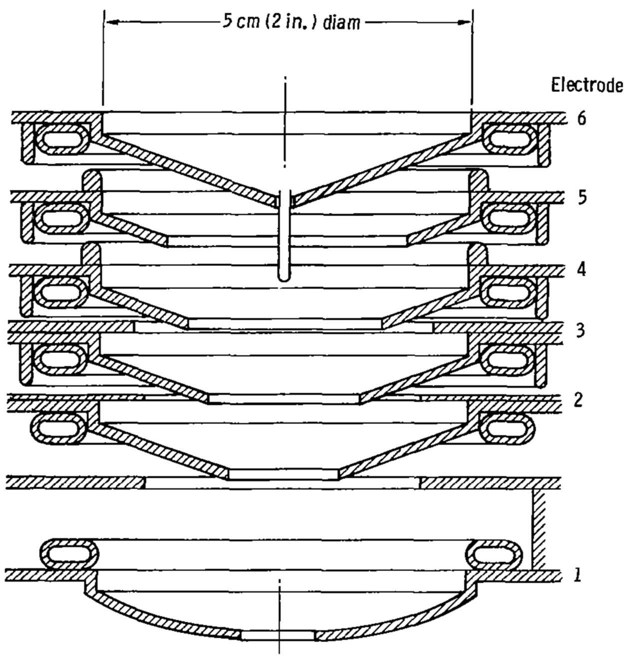
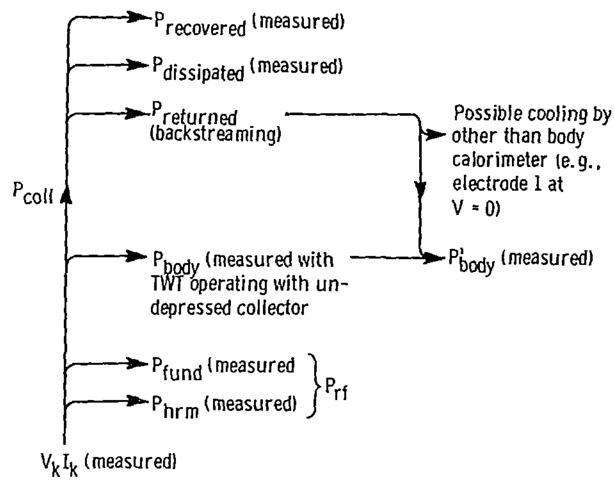


Figure 1. - Multistage depressed collector.



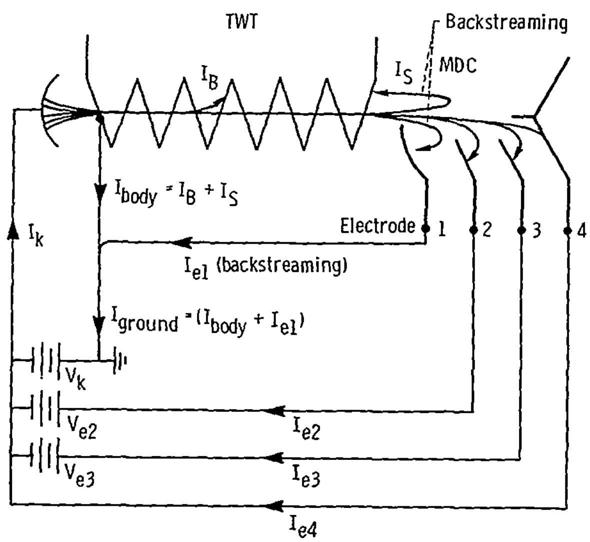
P_{body} = (rf Circuit losses) + (Intercepted power in forward direction)

$P'_{body} = P_{body}$ + (All or part of backstreaming power)

$P_{coll} = V_k I_k - P_{rf} - P_{body}$

Collector efficiency $\equiv \dfrac{P_{recovered}}{P_{coll}}$

(a) Power flow.



Prime power $= V_k (I_{ground}) + \sum_{n=2}^{4} V_{e,n} I_{e,n}$

$P_{recovered} = \sum_{n=2}^{4} \left(|V_k - V_{e,n}| \right) (I_{e,n})$

$P_{coll} = V_k I_k - P_{rf}$ - (Circuit losses) - $(I_B \times \bar{V})$, where $e\bar{V}$ is average energy of intercepted electrons

$P_{coll} \ne V_k I_k - P_{rf}$ - (Circuit losses) - $(I_{ground} \times V_k)$

(b) Electron flow.

Figure 2. - Flow diagrams for TWT with MDC.

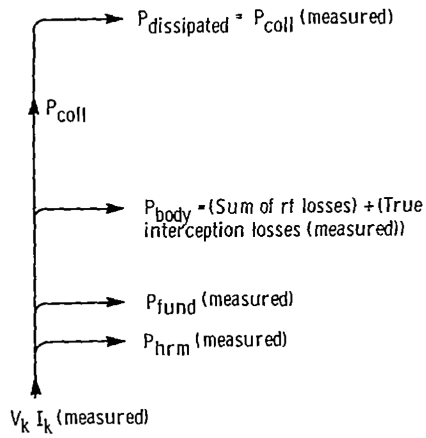


Figure 3. - Power flow diagram for TWT with undepressed collector.

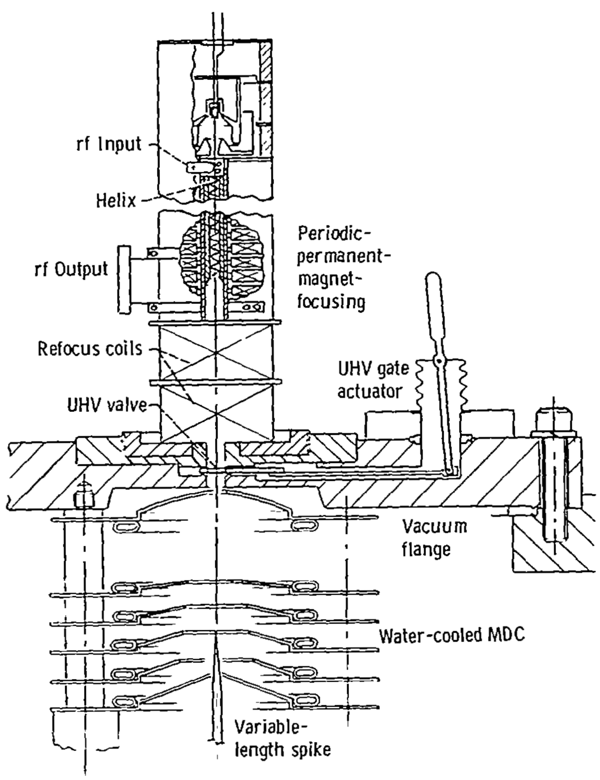


Figure 4. - Schematic of Teledyne MEC TWT model MTZ 7000 with MDC. Frequency, 4.8 to 9.6 GHz; total maximum rf output, 425 W in low mode and 865 W in pulsed-up mode; cathode potential, 9850 V; beam current, 0.365 A in low mode and 0.470 A in pulsed-up mode; duty cycle, 100 percent in low mode and 10 percent in pulsed-up mode.

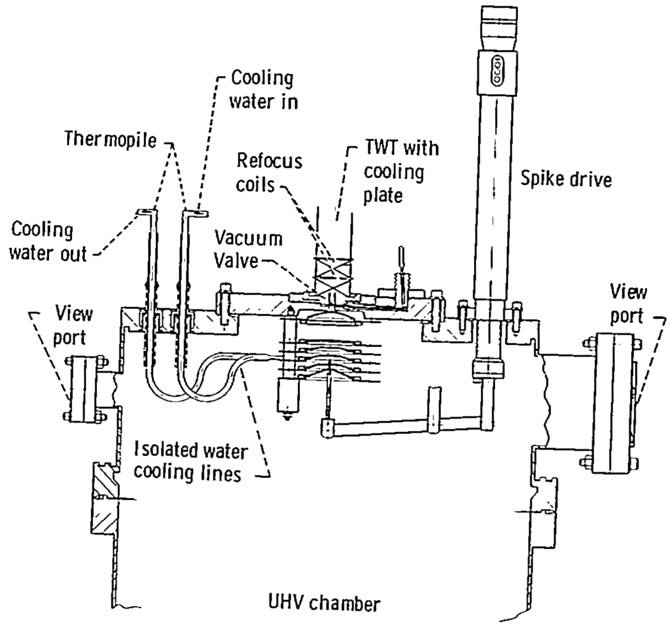


Figure 5. - Schematic of MDC measuring system.

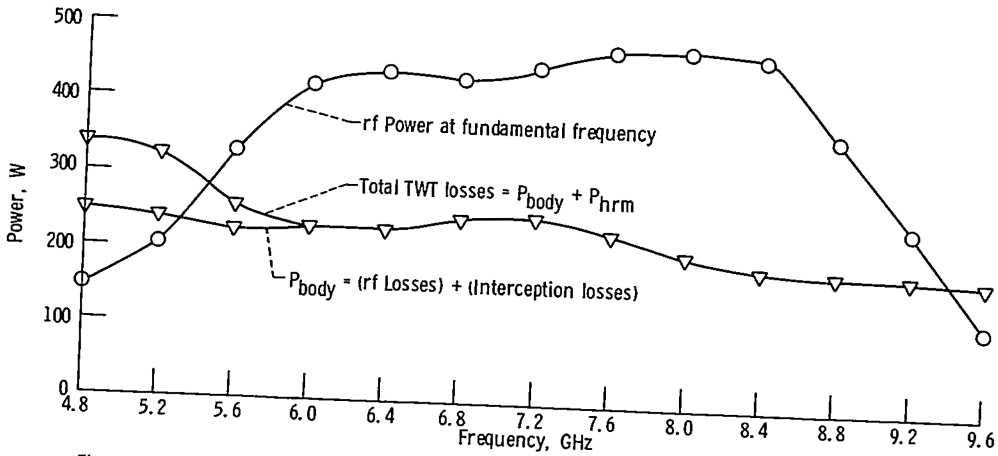


Figure 6. - Radiofrequency power and TWT losses as function of frequency for Teledyne MEC TWT MTZ 7000, serial number 102, at saturation in low mode and duty cycle of 20 percent.

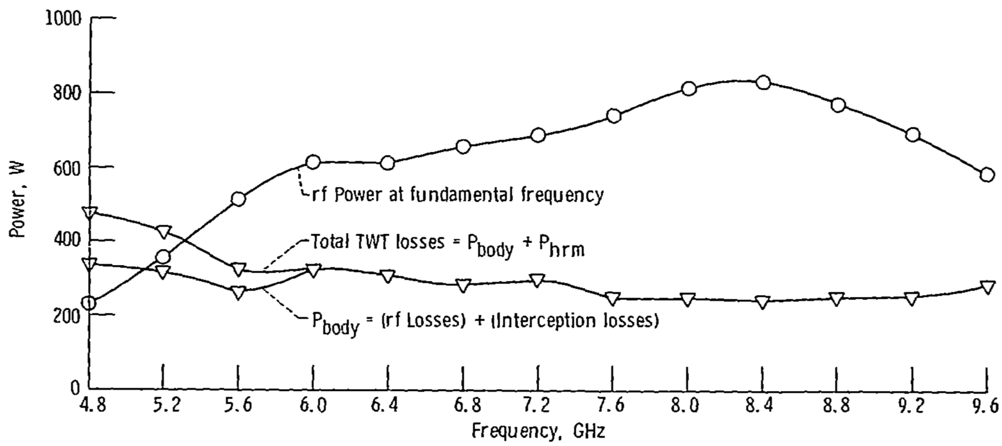


Figure 7. - Radiofrequency power and TWT losses as function of frequency for Teledyne MEC TWT MTZ 7000, serial number 102, at saturation in pulsed-up mode and duty cycle of 10 percent.

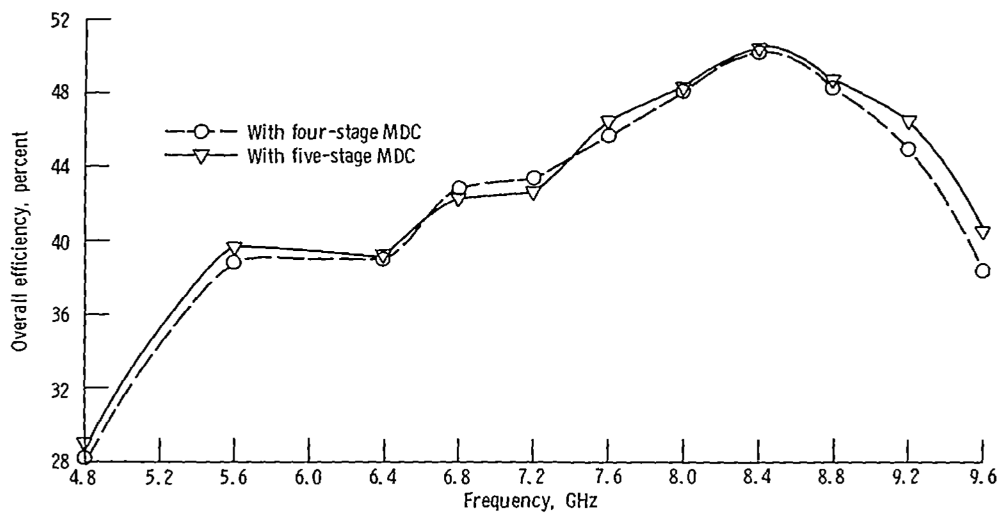


Figure 8. - Overall efficiency (based on total rf output) as function of frequency, at saturation in pulsed-up mode.

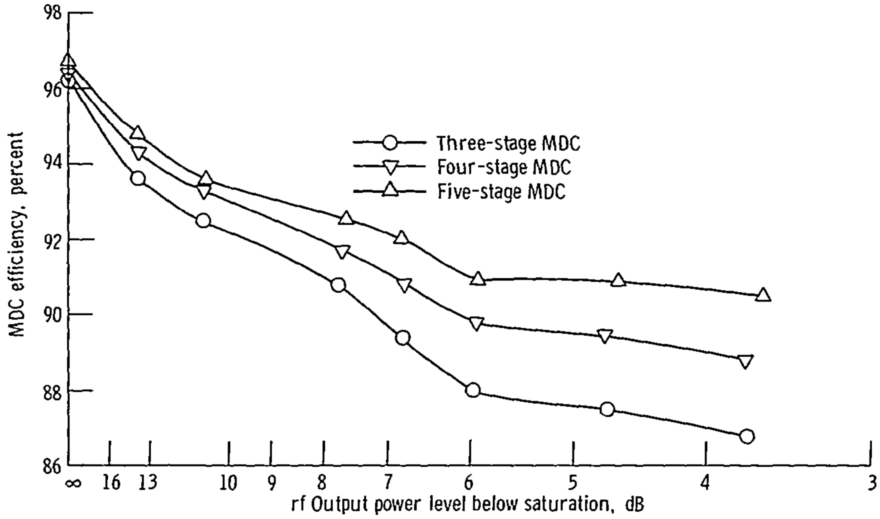


Figure 9. - MDC efficiency as function of rf output power level below saturation, at 8.4 GHz in low mode.

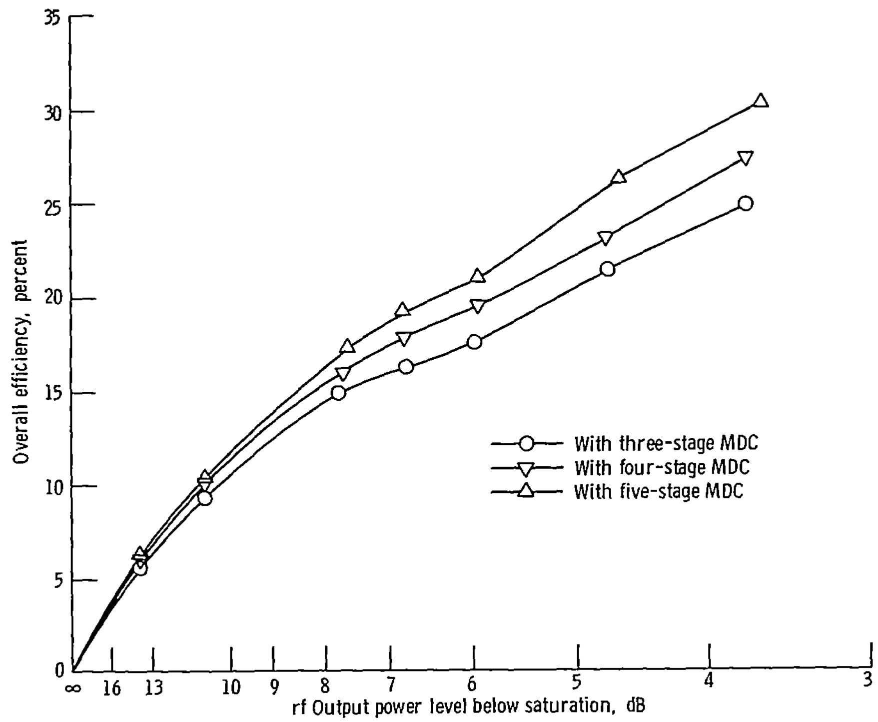


Figure 10. - Overall efficiency as function of rf output power level below saturation, at 8.4 GHz in low mode.

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16. Abstract

An axisymmetric, multistage depressed collector of fixed geometric design was evaluated in conjunction with an octave-bandwidth, dual-mode TWT. The TWT was operated over a wide range of conditions to simulate different applications. The collector was operated in three-, four-, and five-stage configurations, and its performance was optimized (within the constraint of fixed geometric design) over the range of TWT operating conditions covered. For operation of the dual-mode TWT at and near saturation, the collectors increased the TWT overall efficiency by a factor of $2\frac{1}{2}$ to $3\frac{1}{2}$. Collector performance was relatively constant for both the high and low TWT modes and for operation of the TWT across an octave bandwidth. For operation of the TWT in the linear, low-distortion range, collector efficiencies of 90 percent and greater were obtained, leading to a five- to twelvefold increase in the TWT overall efficiency for the range of operating conditions covered and reasonably high (>25 percent) overall efficiencies well below saturation. With collectors of this efficiency it becomes practical to design dual-mode TWT's such that the low mode can represent operation well below saturation. Consequently, the required pulse-up in beam current can be reduced and this mitigates beam control and dual-mode TWT circuit design problems. The improvements in the TWT overall efficiency were somewhat limited (especially at low TWT electronic efficiencies) by excessive beam interception in this particular TWT sample.

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