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SUMMARY

In a joint USAF-NASA program, Lewis Research Center is conducting an efficiency improvement program on 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.

Small, three- and five-stage depressed collectors were evaluated in conjunction with a 4.8- to 9.6-gigahertz TWT of 325- to 675-watt power output and a 0.5-microperv beam. The MDC performed well, even though its design had been optimized for a TWT of identical design but with considerably less output power. Despite large, fixed losses (rf losses, interception losses, and harmonic power generated losses), significant efficiency enhancement was demonstrated with both the three- and five-stage depressed collectors.

At saturated radiofrequency (rf) power output the improvement in the overall efficiency ranged from a factor of 2.5 to 3.0 for the three-stage collector and a factor of 3.0 to 3.5 for the five-stage collector. At saturation, three-stage collector efficiencies (determined directly and without assumptions) of 77 to 80 percent and five-stage collector efficiencies of 81 to 84 percent were obtained across the frequency band. An overall efficiency of 37.0 to 44.3 percent (average, 41.2 percent) across the frequency band of 4.8 to 9.6 gigahertz was demonstrated with the use of harmonic injection. For operation below saturation even larger relative improvements in the overall TWT efficiency and substantially higher MDC efficiencies were demonstrated.

Collector performance was relatively insensitive to the degree of regulation of the collector power supply or to the operating frequency as such.

INTRODUCTION

If the residual energy left in the spent electron beam which exits from a microwave tube could be efficiently recovered, the prime power required to operate the tube could be substantially reduced and the heat dissipation problem mitigated. In a joint USAF-NASA program, Lewis Research Center is conducting an efficiency improvement program on traveling wave tubes (TWT's) for use in electronic countermeasure (ECM) 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 were produced by an analytical process that ties together analyses of the TWT, refocusing system, and MDC. 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 TWT and MDC performance evaluation. MDC efficiencies are determined from measured quantities without any assumptions, and a final system energy balance is obtained.

Previous analytic work (ref. 2) involving TWT performance analysis, refocusing system analysis, and MDC analysis led to specific refocusing system and MDC designs for a 700-watt (peak total rf power conversion), 4.8- to 9.6-gigahertz TWT and predicted three- and five-stage MDC efficiencies of 82 and 85 percent, respectively.

An experimental program was conducted to evaluate and optimize the TWT - refocusing-system - MDC performance (ref. 2). Considerable experimental optimization of the MDC design was required, in part, because of the use of the imperfect TWT input data for the initial computation of TWT performance. This experimental program led to demonstrated MDC efficiencies of 82 and 84 percent for a three- and five-stage MDC, respectively. These results were obtained with a single, rather complex, MDC geometric design consisting of six collecting elements (electrodes; see fig. 1). These include electrodes at ground and cathode potentials. The number of MDC stages is defined as the number of distinct voltages (other than ground) needed to operate the TWT-MDC. In the five-stage configuration, the four collecting elements between ground and cathode potentials were operated at four different voltages; in the three-stage configuration, they were electrically connected as two pairs.

The TWT modified for use in these tests (Teledyne MEC model 5897C, serial number 101; hereinafter called TWT 101 for convenience) exhibited unexpectedly large circuit losses, the effective circuit efficiency being less than 70 percent at some frequencies. Based on cold helix measurements, circuit efficiencies of about 85 percent were expected, indicating the possibility that this TWT was not typical of its class and either had been damaged or deviated from the intended design.

The test program data suggested that with circuit efficiencies of 85 percent, or more, overall TWT efficiencies of over 40 percent were possible across most of the octave bandwidth, where no harmonic power is generated.

The same MDC and refocusing system were then added to a TWT (ser. No. 103) of identical design. The TWT and MDC performances were evaluated at various power levels across the octave bandwidth. The results of these tests are reported later. The TWT failed (apparently, from a failure of the weld between the helix and output coupler) before the test program was completed.

SYMBOLS[1]

I_B	true intercepted current in the forward direction
I_{body}	$I_B + I_S$
I_{coll1}	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 the backstreaming power)
P_{coll}	total power in spent beam that enters MDC
P_{fund}	rf output associated with fundamental frequency
P_{hrm}	rf output resulting from harmonic frequencies
P_{tot}	total rf output, $(P_{fund} + P_{hrm})$
$\bar{V}$	average potential of intercepted electrons
V_k	cathode potential (always negative for work reported herein)

EXPERIMENTAL TWT AND MDC PERFORMANCE EVALUATION

To obtain complete and accurate TWT and MDC performance evaluations, 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 rf losses in the TWT and 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

$$\frac{P_{recovered}}{P_{coll}}$$

With a depressed collector, the possibility exists of backstreaming electrons (I_S and I_{coll1} in fig. 2(b)) returning significant power to the TWT body. Such is the case, in

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

particular, where the undepressed electrode forming the entrace to the depressed collector is not thermally and electrically isolated from 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. (See, for example, ref. 5.)

It should be noted that 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 efficiency

(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

$$P_{coll} = V_k I_k - P_{tot} - \text{(circuit losses)} - (I_B \bar{V})$$

as shown in figure 2.

However, it has been our experience at Lewis that both the circuit efficiency and the true beam interception can vary widely, even between TWT's of identical design. 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 power, or P_{tot}, and P_{body} can be thermally measured, and P_{coll} computed from measured quantities. Since only the total body power P_{body} is needed for the computation of P_{coll}, it can be seen that with this experimental approach the questions of circuit efficiency, true interception, and the average energy of the intercepted electrons are irrelevant.

EXPERIMENTAL TWT

The Teledyne MEC TWT model M5897C S/N 103, as modified for use in this program, and its performance characteristics are shown in figure 4. A refocusing system consisting of two coils has been added, and the TWT is mounted on a 25.4-centimeter (10-in.), ultrahigh vacuum (UHV) flange. The UHV valve shown (ref. 6) was designed to keep the TWT under vacuum during MDC installation and changes, facilitating startup and minimizing cathode activation problems. No valve gate was available for this test, however, and the TWT had to be back-filled with gaseous nitrogen and, after a low-temperature (100° C) bakeout, rf processed under pulsed conditions.

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

EXPERIMENTAL PROGRAM

Bench Test

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

Multistage Depressed Collector Test

In the MDC test setup (fig. 5) the TWT is mounted on a matching flange on a UHV system. The MDC is mounted directly on the UHV flange that houses the TWT and vacuum valve. Each MDC electrode, including the undepressed electrode, is thermally and electrically isolated and is 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 drives a variable-length spike. Over its range of variability, the length of the spike significantly affects the electric field distribution within the collector, and its optimum length can be established quickly and easily for each MDC configuration. Since the refocusing coils and pole pieces are outside the vacuum, they can be manipulated and moved over their designed range of variability while the TWT is operating. Together with variation of the refocusing coil currents, this enables the rapid optimization, within limits, of the refocusing field profile. Once established, this profile can 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 (i.d., 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 will have to 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 provides an analog real-time readout of the recovered power as any of the system variables are changed while the TWT is operating. These variables are the individual collector stage voltages, the refocusing coil currents, the polepiece locations, and the spike length.

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

EXPERIMENTAL RESULTS

Bench Test Results

The rf output power at the fundamental frequency, the TWT body losses (sum of rf losses and interception losses), and total, fixed TWT losses (sum of TWT body losses and harmonic power generated) versus frequency are shown in figure 6.

The TWT 103 generates significantly more rf power than TWT 101 in the frequency range of 6.4 to 9.6 gigahertz. Its peak electronic efficiency exceeds 19 percent (compared with 17 percent for TWT 101). While this aids in obtaining high overall efficiencies, lower MDC efficiencies can be expected when operating TWT 103 at saturation. Moreover, the large total fixed losses of TWT 103 substantially limit the improvement in the overall efficiency obtainable with a depressed collector.

To calculate the circuit efficiency of the TWT (circuit efficiency is defined as the ratio of rf power output at the load terminal at a given frequency to the total rf power generated within the tube at the same frequency), it is necessary to make an assumption about the average energy of the intercepted electrons. Table I shows the circuit efficiency of TWT 103 at saturation and at the rated output power as a function of frequency for an average intercepted electron energy of 0.8 eV_k. Where harmonic power is generated, the circuit efficiency is based on the total rf power generated, since it is impossible to separate the contributions to the total circuit losses due to P_{fund} and P_{hrm}. Shown also are the circuit efficiencies at saturation of TWT's 101 and 102 for purposes of comparison. (TWT 102, a third TWT of the same type, was also bench tested with an undepressed collector.) It is evident that

(1) None of the TWT's exhibit rf losses that are strictly of the $(\text{frequency})^{1/2}$ type

(2) At fixed frequencies the total rf losses of TWT's of identical design vary widely (up to a factor of 1.8)

(3) The large differences in circuit efficiency of TWT 103 at saturation and at the rated output power (where these powers vary appreciably) imply considerable heating of the helix at saturation.

Multistage Depressed Collector Test Results

After the bench test MDC 1WX5 was added to TWT 103, and the combination evaluated. The MDC was operated as both a three-stage and five-stage collector. Two types of optimizations were stressed: Maximizing overall efficiency across the frequency band when operating at or very near to saturation, and minimizing the prime power required when operating at the rated rf power output of 400 watts at the fundamental frequency across the frequency band (except at 4.8 GHz where TWT 103 produced only 330 W). Overall efficiency, based on both the rf power generated at the fundamental frequency P_{fund} and on the total rf power generated P_{tot}, was determined, the latter being indicative of performance obtainable with excellent harmonic suppression.

The TWT failed before completion of the test program. A fairly complete optimization (for the existing MDC geometrical design) was obtained with input drive at the fundamental frequency. Only very limited data were obtained with harmonic injection (with input drive at both the fundamental and second harmonic frequencies).

Final Energy Balance of the TWT-MDC System

An example of the data obtained and the energy (power) balance established at a specific operating point is shown in table II. Total backstreaming produced by the MDC is 29.9 milliamperes. If the actual backstreaming power of 173 watts is ignored, a collector efficiency of 83.4 percent (4.4 percentage points too large) would result. If, however, $I_B + I_S + I_{coll1}$ were considered as beam interception at an average energy of eV_k, as was done in reference 7, for example, the collector efficiency calculated would be 86.1 percent, a gross exaggeration. With these assumptions, the five-stage collector efficiency (at this operating point) is calculated to be 83.6 percent, 1.4 percentage points too large. It should be noted that the improperly computed three-stage collector efficiency is significantly larger than the improperly computed five-stage collector efficiency. This is due to the much larger amount of backstreaming produced by the three-stage collector. Clearly, without the correct understanding and evaluation of the effects of backstreaming produced by the collectors, completely erroneous conclusions could be drawn.

It is evident from a comparison of I_S and I_{coll1} in table II that more than half (two thirds is more typical) of the backstreaming current is collected on the undepressed collector electrode. Having this electrode electrically isolated from the TWT body (not a common practice) is highly useful for the following considerations: Every depressed collector operating at maximum efficiency produces some backstreaming; and if only $I_{ground} = I_B + I_S + I_{coll1}$ (see fig. 2(b)) can be measured, premature fear of helix burnout may prevent sufficient collector depression for maximum efficiency.

Comparison of MDC Performance with TWT's 101 and 103

To evaluate the repeatability in MDC performance with two TWT's of identical design and similar performance, TWT 103 was operated at 8.4 gigahertz at an rf output level corresponding to an electronic efficiency of 17.0 percent. The MDC 1WX5 geometric design (and the variables already discussed) was optimized for this operating point with TWT 101. The MDC performance for the same geometric design was reoptimized with TWT 103 at this point. Setting up completely identical conditions was not possible because the TWT operating cathode voltages and currents differ somewhat and the refocusing system tunnels are not identical. The results are shown in table III. The measured rf powers differ because of differences in circuit efficiency and beam power. The MDC performances are comparable. The MDC operating voltages (each set optimized for each TWT) were similar, indicating that the two spent beams have somewhat similar velocity distributions. For slightly higher rf power levels, the MDC efficiency dropped steadily, indicating that this MDC design is not optimum for higher TWT electronic efficiencies.

Performance at Saturation

Based on initial tests and an evaluation of fixed TWT losses, saturated operation at 6.4 gigahertz was selected as the operating point for MDC optimization. Data were then taken (at this fixed set of operating conditions) across the frequency band at saturation.

The overall efficiency based on P_{tot} and the MDC efficiency versus frequency are shown in figure 7. With the five-stage MDC, overall efficiencies range from 37.0 to 44.3 percent. Over much of the band, the overall efficiency based on P_{tot} exceeds 40 percent. The MDC efficiency ranges from 81.4 to 84.2 percent.

With the three-stage MDC, the overall efficiency based on P_{tot} ranges from 32.5 to 40.7 percent. The MDC efficiency ranges from 77.0 to 80.4 percent.

The overall TWT efficiency based on P_{fund} (for the same set of data as above) is shown in figure 8. In the range 4.8 to 6.2 gigahertz this overall efficiency is substantially lower than that based on P_{tot} because of the large amount of harmonic power generated by TWT 103.

As discussed previously and as can be seen from figure 6, the large, fixed TWT losses (including harmonic power) in the frequency range 4.8 to 6.2 gigahertz preclude the achievement of high overall efficiency without harmonic injection.

Both with the three- and five-stage MDC, the optimum set of collector voltages with TWT 103 differs significantly from that with TWT 101, indicating that, at saturation, the spent-beam velocity distribution differs substantially between TWT 101 and 103. The five-stage MDC voltages with TWT 103 are spread out much more evenly between the cathode voltage V_k and 0.5 V_k. Therefore, the velocity distribution at saturation no longer exhibits two peaks, which for TWT 101 made the three-stage MDC almost as good as the five-stage MDC (ref. 2). With TWT 103 the difference between three- and five-stage MDC efficiencies is 3.8 to 4.4 percentage points.

The collector voltages and final current distributions (including all backstreaming) across the frequency band are shown in table IV. The current distribution is much more sensitive to the total rf power being produced than to the operating frequency as such. Total backstreaming ($I_S + I_{coll1}$) averages about 8 percent of I_k for the three-stage collector and 3 to 4 percent of I_K for the five-stage collector.

Performance at P_{fund} = 400 W

An experimental program was conducted to minimize the prime power needed to operate the TWT across the frequency band (4.8 to 9.6 GHz) at the rated output power (and fundamental frequency) of 400 watts.

Optimizing the MDC performance at 4.8 or 5.2 gigahertz was indicated, the former giving the lowest overall efficiency because of the low output power (330 W), the latter resulting in the highest total rf power (P_{tot}) generated (540 W) in order to produce 400 watts (P_{fund}) at 5.2 gigahertz.

The TWT and MDC (three and five stage) performance is shown in figure 9. The five-stage MDC was optimized at 4.8 gigahertz, saturated output. The overall efficiency based on P_{fund} ranges from 28.3 to 39.0 percent. If TWT 103 generated 400 watts at 4.8 gigahertz, a minimum overall efficiency of about 30 percent could be expected. The improvement in the overall efficiency due to the five-stage MDC is by a factor of 3.5 to 4.0. The five-stage MDC efficiencies range from 84.0 to 86.1 percent.

The three-stage MDC efficiency was optimized at 5.2 gigahertz. The overall efficiency ranges from 25.2 to 34.1 percent. Use of the three-stage MDC improved the overall efficiency by a factor of 3.0 to 3.5. The three-stage MDC efficiencies range from 80.6 to 82.5 percent.

The three-stage collector voltages and final current distributions across the frequency band are shown in table V(a). In the range of 5.6 to 9.6 gigahertz, where the total rf power produced is relatively constant (there are differences because the circuit efficiency and P_{hrm} are functions of frequency), the current distribution is relatively insensitive to frequency. Consequently, the MDC performance is almost constant across the octave bandwidth.

The five-stage depressed collector voltages and final current distributions are shown in table V(b). The current distribution in the five-stage collector is more sensitive to frequency than in the three-stage collector. The collector efficiency, however, is almost constant across the octave bandwidth. A typical refocusing field profile used in all these tests with TWT 103 is shown in figure 10.

Experiments with Harmonic Injection

Only very limited experiments were performed using harmonic injection because TWT 103 failed shortly after the testing was started. Much of the testing was done at 4.8 gigahertz (the worst point in terms of relative amount of harmonic power generated).

At 4.8 gigahertz harmonic injection was very effective, not only in reducing the relative amount of harmonic power generated, but also in substantially increasing the output power at the fundamental frequency. Without harmonic injection, TWT 103 simultaneously generated 330 watts at 4.8 gigahertz and 155 watts at 9.6 gigahertz. With harmonic injection rf power output at 4.8 gigahertz was raised to 530 watts and that at 9.6 gigahertz reduced to 48 watts.

At other frequencies the gains were smaller, but the testing had only begun. At 6.4 gigahertz where only a few watts of harmonic power were generated, harmonic injection resulted in significantly decreasing the TWT body power.

The results, in terms of the overall efficiency based on P_{fund} as a function of frequency, are shown in figures 8 and 9. A dramatic improvement is evident. It is believed that, with further optimization, the overall efficiency could be increased to 40 percent or more across much of the lower part of the frequency band. However, a minimum overall efficiency (based on P_{fund}) of 37 percent was demonstrated across the frequency band of 4.8 to 9.6 gigahertz.

At the $P_{fund} = 400$ watts level, data were obtained only at 4.8 gigahertz (previously, the worst point). The overall efficiency was raised from 28.3 to 37.3 percent. It is believed that significant improvement could also be obtained up to 6.4 gigahertz, as it was for saturated operation.

Prime Power Required

The prime power required by TWT 103 at saturation as a function of frequency is shown in figure 11. A maximum of 1600 watts is required with a three-stage collector, and 1450 watts with a five-stage collector. If only 400 watts at the fundamental frequency is needed across the band, the maximum prime power required can be decreased to 1370 and 1220 watts for a three- and five-stage MDC, respectively, without the use of harmonic injection. The prime power required versus frequency is shown in figure 12. Limited testing with harmonic injection indicated that the maximum prime power required (using a five-stage MDC) could be reduced by approximately an additional 80 watts.

Collector Voltage Variations

The degree of voltage regulation required for the collector power supply was evaluated by determining the performance of the TWT 101 and MDC as a function of collector voltages. For both the three- and five-stage collectors and for the simplified three-stage MDC described in reference 2, all the collector voltages (except the electrode at cathode potential) were varied by fixed ratios above and below the nominal settings. The results are shown in figure 13. The total range covered can be considered as ±8 percent from an intermediate setting, which would correspond to an unregulated power supply. For both the three- and five-stage collectors, only a 1-percentage-point reduction in the overall TWT efficiency results for a ±3-percent collector voltage regulation.

MDC Performance for TWT 101 Operation Below Saturation

In the previous sections of this report, MDC performance optimizations at the TWT operating point that produces the greatest disorder in the spent beam have been stressed. There are, however, circumstances when different optimizations become important; for example, when

(1) A large pulse-up capability is needed and the continuous wave (CW) mode represents TWT operation below saturation.

(2) 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 TWT and MDC performance at conditions that represent a reasonable compromise between these extreme limits, both three- and five-stage MDC performances were optimized at the low-band-edge, saturated output. The results (at this fixed set of operating conditions) are shown in table VI. The collector efficiency, for operation increasingly below saturation, rises asymptotically to 91.5 and 92.5 percent for the three- and five-stage collectors, respectively. With both, the overall TWT efficiency remains relatively high for operating points well below saturation.

The current distribution in the three- and five-stage collectors as a function of the TWT output power level at 8.4 gigahertz between the zero and maximum output is shown in table VII. The MDC power supply must be designed to handle the full range of currents shown, unless the TWT is always driven to or near saturation. When optimized for the dc beam, the MDC efficiency exceeded 94 percent for both MDC's. To obtain even higher dc collector efficiencies, however, the geometric design of the MDC's would have to be modified to produce less dispersion (radial deflection).

CONCLUDING REMARKS

Small, three- and five-stage depressed collectors were evaluated in conjunction with a 4.8- to 9.6-gigahertz TWT of 325 to 675 watt output power. Despite large, fixed TWT losses, significant efficiency enhancement was demonstrated with both the three- and five-stage MDC. At saturated rf output, the improvement in the overall efficiency ranged from a factor of 2.5 to 3.0 for the three-stage MDC and from a factor of 3.0 to 3.5 for the five-stage depressed collector. The collector performance and collector current distribution were more a function of the total rf power generated by the TWT than of the operating frequency as such.

An overall efficiency of 37.0 to 44.3 percent across the frequency band of 4.8 to 9.6 gigahertz was demonstrated with the use of harmonic injection.

The MDC design was optimized for a TWT of lower electronic efficiency. Consequently, significant improvement in performance could be expected with further optimization of MDC design. However, with a TWT of such low electronic efficiency and small collectors of relatively few stages, the fixed TWT losses would have to be reduced in order to obtain very high overall efficiencies (in the range of 50 percent).

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TABLE I. - CIRCUIT EFFICIENCY[a] FOR TELEDYNE MEC

TWT MODEL 5897C

[Intercepted power = $I_B \times 0.8\ V_k$.]

Frequency, GHz	TWT 101	TWT 102	TWT 103	
	At saturation			At P_{fund} = 400 W
	Circuit efficiency, percent			
4.8	84.8	85.2	87.1	87.1
5.2	85.2	90.1	88.9	89.4
5.6	84.9	90.0	85.2	89.4
6.0	79.7	87.6	78.0	86.1
6.4	75.0	85.1	76.6	82.5
6.8	72.6	83.2	84.0	90.5
7.2	68.9	78.6	80.9	89.4
7.6	69.7	78.9	81.6	88.4
8.0	72.0	82.5	80.1	87.2
8.4	74.9	83.1	78.1	85.7
8.8	74.2	83.0	77.3	84.7
9.2	72.3	80.0	75.3	80.3
9.6	68.1	78.0	75.4	75.9

[a]Based on total rf power output.

TABLE II. - RESULTS FOR TWT 103 WITH THREE-STAGE MDC 1WX5 DEMONSTRATING FINAL ENERGY BALANCE AT A REPRESENTATIVE FREQUENCY

(a) Tube test conditions and results

Frequency, GHz	8.000
P_{in}, mW	10.73
P_{tot}, W	637
P_{fund}, W	637
P_{hrm}, W	0
Gain, dB	47.7
V_k, V	-9300
I_k, mA	450.4
Beam power, W	4190.8
P_{body}, W	231
P'_{body}, W	254
I_B, mA	7.2
I_S, mA	12.6

(b) MDC test conditions and results

Collector stage	Voltage, V	Current, mA	Power, W	
			Recovered	Dissipated
1	0	17.3	0	100
2	-5060	76.4	387	60
3	-5060	167.2	846	206
4	-8195	15.7	129	54
5	-8195	150.5	1233	153
6	-9300	3.2	30	52
Total			2625	625
Collector efficiency, 79.0 percent Overall efficiency, 40.7 percent				

(c) Final energy balance

Useful rf power, W	637
TWT body losses, W	231
Backstreaming to TWT body, W	23
Backstreaming to refocusing tunnel, W	50
Backstreaming to undepressed collector, W	100
Collector (2 to 6) dissipation, W	525
Recover Power, W	2625
Total	4191

TABLE III. - PERFORMANCE COMPARISON OF TWT's 101 AND 103 WITH MDC 1WX5 (FIVE STAGE)

	TWT 101	TWT 103
P_{tot},[a] W	513	561
Body power, W	198	208
Overall efficiency, percent	41.6	44.3
Collector efficiency, percent	84.2	85.1

[a]At an electronic efficiency of 17.0 percent at 8.4 GHz.

TABLE IV. - CURRENT DISTRIBUTIONS FOR TWT 103 WITH

MDC 1WX5 AT SATURATION

(a) Three-stage MDC. (Also see fig. 1.) Collector voltages: Collector 1 = 0; 2 = 0.54 V_k; 3 = 0.54 V_k; 4 = 0.88 V_k; 5 = 0.88 V_k; 6 = V_k (cathode potential)

Frequency, GHz	Current, mA							
	I_B	I_S	I_{coll1}	I_{coll2}	I_{coll3}	I_{coll4}	I_{coll5}	I_{coll6}
4.8	9.7	9.7	26.2	44.5	97.8	13.0	244.7	3.8
5.2	9.3	10.0	26.6	48.8	123.0	12.8	215.8	3.3
5.6	9.7	10.7	28.3	52.5	128.9	12.4	203.7	3.8
6.0	10.7	7.8	26.9	47.8	139.1	15.1	198.9	3.5
6.4	9.3	7.6	22.2	54.0	159.6	19.0	174.7	3.7
6.8	8.7	9.0	29.5	53.4	173.2	16.3	153.9	5.9
7.2	7.3	12.4	23.6	63.7	174.2	15.3	148.6	4.7
7.6	7.7	11.7	18.7	71.5	169.7	16.1	149.6	4.6
8.0	7.2	12.6	17.3	76.4	167.2	15.7	150.5	3.2
8.4	7.5	12.5	17.3	80.1	163.6	16.7	151.0	1.3
8.8	7.3	10.6	17.1	81.5	144.6	16.7	171.3	1.1
9.2	7.4	9.8	18.1	73.3	131.1	17.1	192.6	.9
9.6	7.1	10.6	19.5	56.3	109.4	18.1	227.9	1.4

(b) Five-stage MDC. (Also see fig. 1.) Collector voltages: collector 1 = 0; 2 = 0.50 V_k; 3 = 0.56 V_k; 4 = 0.77 V_k; 5 = 0.92 V_k; 6 = V_k (cathode potential)

Frequency, GHz	Current, mA							
	I_B	I_S	I_{coll1}	I_{coll2}	I_{coll3}	I_{coll4}	I_{coll5}	I_{coll6}
4.8	9.7	2.9	17.5	61.6	94.9	45.2	210.0	8.1
5.2	9.3	4.3	17.0	67.2	107.2	43.7	195.5	8.4
5.6	9.7	4.9	18.9	72.1	120.1	42.1	174.1	8.0
6.0	10.7	1.7	18.5	63.3	122.2	49.6	175.7	8.4
6.4	9.3	2.3	14.6	61.6	147.6	64.3	143.3	8.2
6.8	8.7	4.3	17.3	68.2	159.4	46.2	134.6	13.6
7.2	7.3	4.1	12.2	82.2	159.4	51.6	122.1	12.3
7.6	7.7	3.5	9.7	86.0	153.5	52.4	127.9	12.0
8.0	7.2	2.8	9.1	91.8	157.6	60.8	112.0	9.9
8.4	7.5	2.1	9.1	95.7	149.4	63.9	116.8	8.1
8.8	7.3	1.3	8.7	98.0	129.5	61.3	138.0	6.0
9.2	7.4	1.6	9.7	91.0	119.9	62.1	155.4	5.4
9.6	7.1	2.3	11.1	74.1	101.5	63.3	186.3	5.1

TABLE V. - CURRENT DISTRIBUTIONS FOR TWT 103 WITH MDC 1WX5

AT [a]P_{fund} = 400 W

(a) Three-stage MDC. (Also see fig. 1.) Collector voltages: collector 1 = 0; 2 = 0.52 V_k; 3 = 0.52 V_k; 4 = 0.92 V_k; 5 = 0.92 V_k; 6 = V_k (cathode potential)

Frequency, GHz	Current, mA							
	I_B	I_S	I_{coll1}	I_{coll2}	I_{coll3}	I_{coll4}	I_{coll5}	I_{coll6}
4.8	11.2	7.7	21.1	41.0	123.8	11.6	228.4	6.7
5.2	9.9	9.3	22.0	45.7	132.6	9.8	213.9	8.4
5.6	8.8	11.4	23.2	49.7	99.4	12.0	237.5	8.8
6.0	8.8	10.8	21.2	49.9	104.3	13.4	232.7	9.4
6.4	8.6	7.7	13.8	45.5	116.6	14.2	234.2	10.4
6.8	8.7	8.2	22.4	44.7	91.2	16.3	242.8	16.0
7.2	7.8	8.9	20.5	48.2	92.2	14.6	244.2	13.8
7.6	7.0	9.8	18.3	49.0	91.6	14.2	248.1	12.0
8.0	6.8	9.9	16.0	49.6	99.6	14.6	243.3	10.8
8.4	6.7	9.3	14.6	48.8	97.1	14.7	251.0	8.2
8.8	6.8	9.4	13.8	48.2	101.5	14.4	249.1	6.4
9.2	7.1	10.4	16.0	46.8	111.9	15.5	236.6	5.7
9.6	7.9	9.8	15.6	48.4	121.8	16.1	224.5	5.6

[a]At 4.8 GHz P_{fund} = 329 W at saturation.

(b) Five-stage MDC. (Also see fig. 1.) Collector voltages: collector 1 = 0; 2 = 0.48 V_k; 3 = 0.55 V_k; 4 = 0.83 V_k; 5 = 0.94 V_k; 6 = V_k (cathode potential)

Frequency, GHz	Current, mA							
	I_B	I_S	I_{coll1}	I_{coll2}	I_{coll3}	I_{coll4}	I_{coll5}	I_{coll6}
4.8	11.2	1.2	15.8	63.0	98.4	46.4	202.7	12.8
5.2	9.9	2.7	16.4	66.7	104.9	44.8	193.1	13.4
5.6	8.8	3.8	18.3	73.1	74.0	47.1	210.0	16.1
6.0	8.8	3.4	18.7	70.6	80.3	48.9	203.7	17.0
6.4	8.6	3.2	10.5	57.9	102.3	56.3	194.5	18.5
6.8	8.7	1.3	15.2	63.5	72.4	53.9	211.9	24.2
7.2	7.8	2.2	14.2	65.1	74.2	52.8	212.9	22.1
7.6	7.0	2.8	11.9	64.9	75.8	54.9	213.4	21.1
8.0	6.8	2.4	10.3	66.5	74.0	56.7	216.3	18.9
8.4	6.7	1.9	8.9	68.8	75.2	57.2	215.8	16.7
8.8	6.8	1.6	8.3	68.6	76.6	57.0	219.2	12.8
9.2	7.1	1.2	8.3	63.7	91.1	56.5	212.9	10.5
9.6	7.9	.9	10.5	61.4	97.1	63.5	199.8	10.3

[a]At 4.8 GHz P_{fund} = 333 W at saturation.

TABLE VI. - TWT 101 PERFORMANCE WITH MDC 1WX5

(OPTIMIZED AT 4.8 GHz AT SATURATION)

(a) Three-stage MDC

Frequency, GHz	Overall efficiency,[a] percent		Collector efficiency, percent
	Without MDC	With MDC	
4.8:			
Saturation	6.9	23.7	82.4
-3 dB	3.5	19.0	86.8
-6 dB	1.7	11.2	87.6
-9 dB	.8	6.3	88.5
8.4:			
Saturation	12.5	36.9	80.2
-3 dB	6.3	28.4	85.2
-6 dB	3.1	17.2	86.1
-9 dB	1.5	9.6	87.0
9.6:			
Saturation	8.3	30.5	83.4
-3 dB	4.2	21.0	85.6
-6 dB	2.1	12.2	86.2
-9 dB	1.1	7.6	87.9
dc beam	----	----	91.5

(b) Five-stage MDC

Frequency, GHz	Overall efficiency,[a] percent		Collector efficiency, percent
	Without MDC	With MDC	
4.8:			
Saturation	7.1	26.7	84.8
-3 dB	3.5	21.0	88.6
-6 dB	1.7	13.0	89.4
-9 dB	.9	7.5	90.4
8.4:			
Saturation	12.7	39.2	82.0
-3 dB	6.4	31.1	87.0
-6 dB	3.2	20.3	88.6
-9 dB	1.6	12.0	89.5
9.6:			
Saturation	8.4	33.0	85.4
-3 dB	4.3	23.9	88.0
-6 dB	2.1	14.7	89.0
-9 dB	1.1	9.3	90.4
dc beam	----	----	92.9

[a]Based on rf output power at the fundamental frequency.

TABLE VII. - CURRENT DISTRIBUTIONS FOR TWT 101 AT 8.4 GHz WITH MDC 1WX5 (OPTIMIZED AT 4.8 GHz AT SATURATION)

(a) Three-stage MDC. (Also see fig. 1.) Collector voltages: collector 1 = 0; 2 = 0.54 V_k; 3 = 0.54 V_k; 4 = 0.93 V_k; 5 = 0.93 V_k; 6 = V_k (cathode potential)

Operating condition	Current, mA							
	I_B	I_S	I_{coll1}	I_{coll2}	I_{coll3}	I_{coll4}	I_{coll5}	I_{coll6}
Saturation	3.91	14.0	15.8	52.0	163.1	12.9	152.9	15.0
-3 dB	3.29	6.9	8.0	27.5	94.8	13.1	266.0	10.4
-6 dB	3.26	6.5	4.2	12.5	70.6	23.6	304.0	4.0
-9 dB	[a]12.0		3.4	4.6	48.8	33.0	327.8	1.0
dc	2.94	3.5	1.2	1.8	3.1	25.2	392.9	-.2

[a]No bench test data are available at -9 dB; therefore I_B and I_S cannot be determined separately.

(b) Five-stage MDC. (Also see fig. 1.) Collector voltages: collector 1 = 0; 2 = 0.51 V_k; 3 = 0.57 V_k; 4 = 0.86 V_k; 5 = 0.94 V_k; 6 = V_k (cathode potential)

Operating condition	Current, mA							
	I_B	I_S	I_{coll1}	I_{coll2}	I_{coll3}	I_{coll4}	I_{coll5}	I_{coll6}
Saturation	3.91	10.1	11.3	68.7	88.5	49.5	186.0	11.7
-3 dB	3.29	5.4	8.4	25.5	37.7	69.0	271.5	8.6
-6 dB	3.26	4.6	2.2	7.6	34.8	78.7	295.7	1.0
-9 dB	[a]7.60		1.2	3.2	15.8	98.2	303.4	-.1
dc	2.94	.7	.8	3.0	1.4	48.5	372.1	-.4

[a]No bench test data are available at -9 dB; therefore, I_B and I_S cannot be determined separately.

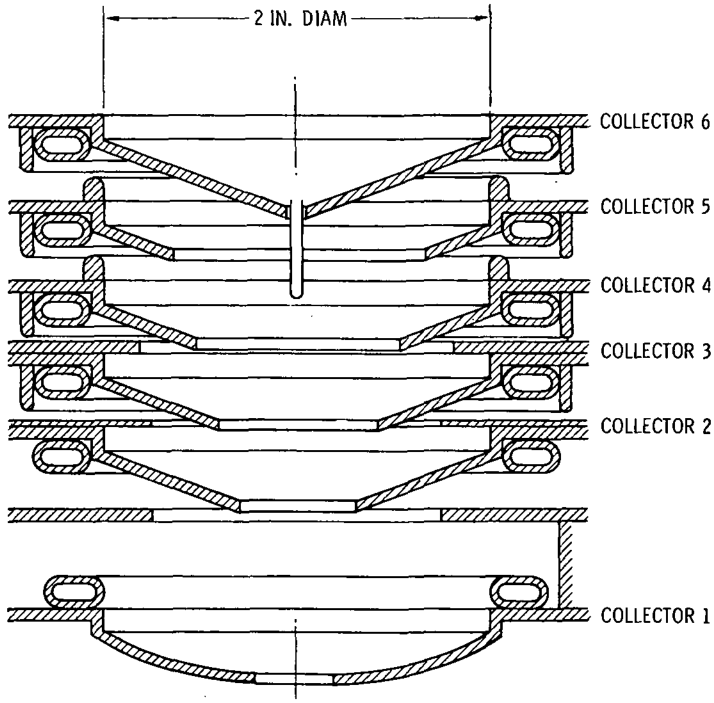
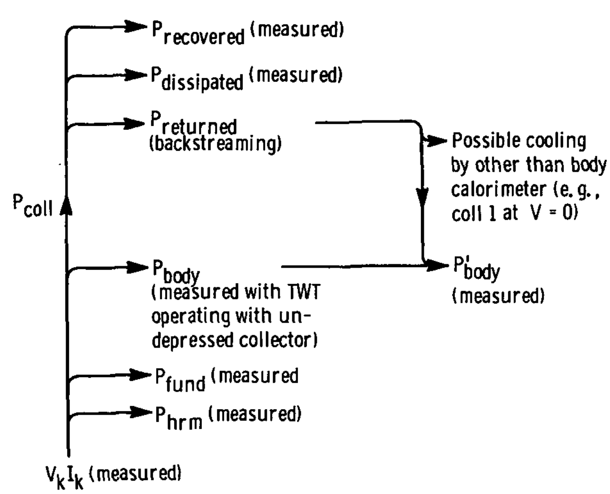


Figure 1. - Multistage depressed collector (design 1WX5).



P_{body} = (rf circuit losses) + (intercepted power in forward direction)

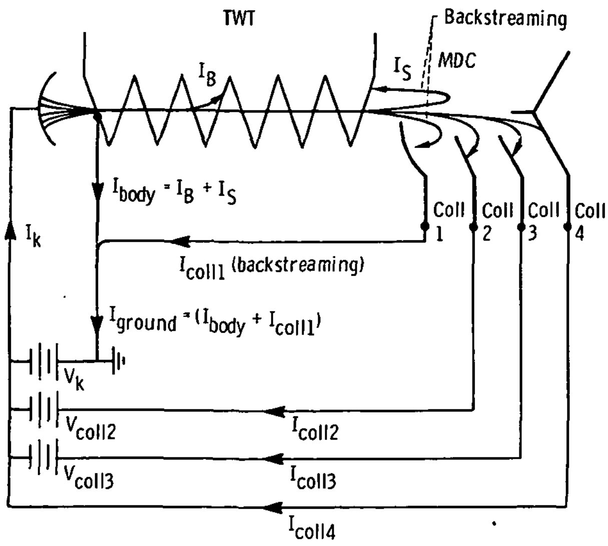
$P'_{body} = P_{body}$ + (all or part of backstreaming power)

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

$$\text{Collector efficiency} \equiv \frac{P_{recovered}}{P_{coll}}$$

(a) Power flow.

Figure 2. - Flow diagrams for TWT with MDC.



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

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

$P_{coll} = V_k I_k - P_{tot} - (\text{circuit losses}) - (I_B \times \overline{V}^{*})$

$P_{coll} \neq V_k I_k - P_{tot} - (\text{circuit losses}) - (I_{ground} \times V_k)$

*$e\overline{V}$ is average energy of intercepted electrons

(b) Electron flow.

Figure 2. - Concluded.

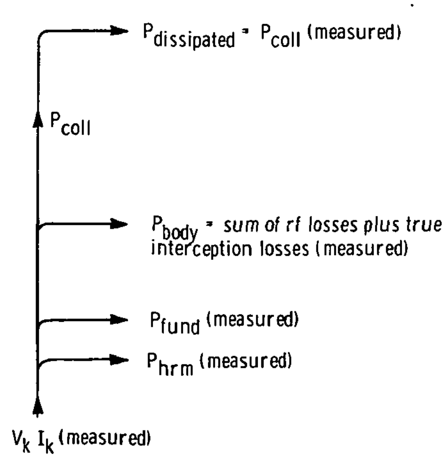


Figure 3. - Power flow diagram for TWT with undepressed collector.

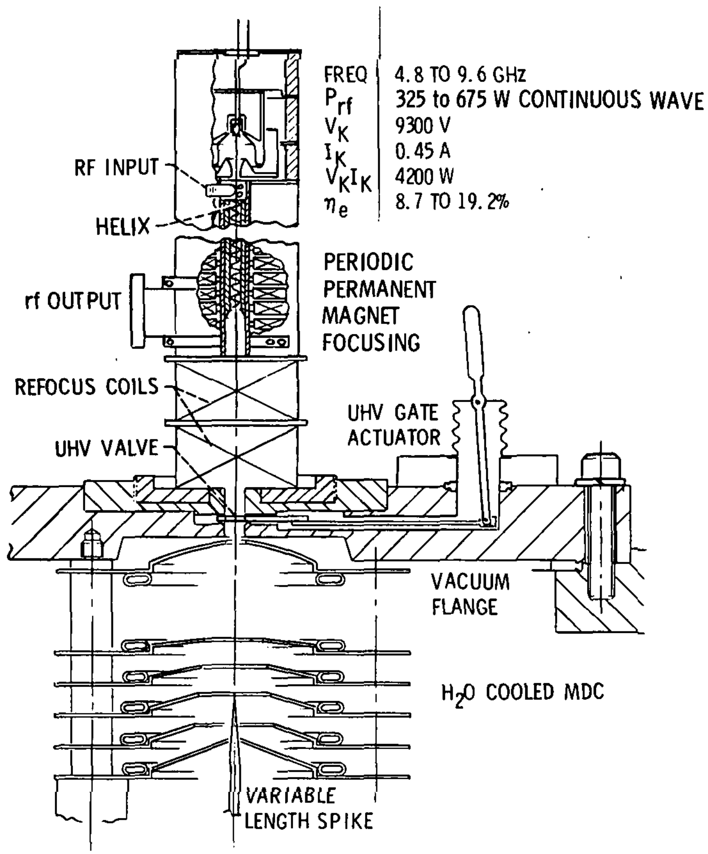


Figure 4. - MEC TWT type M5897C schematic with MDC.

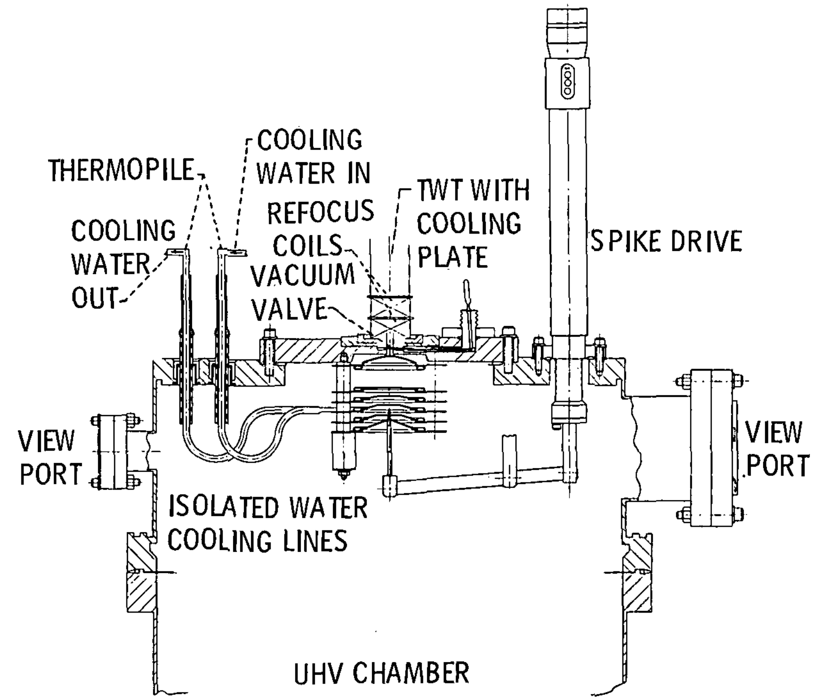


Figure 5. - Schematic of MDC measuring system.

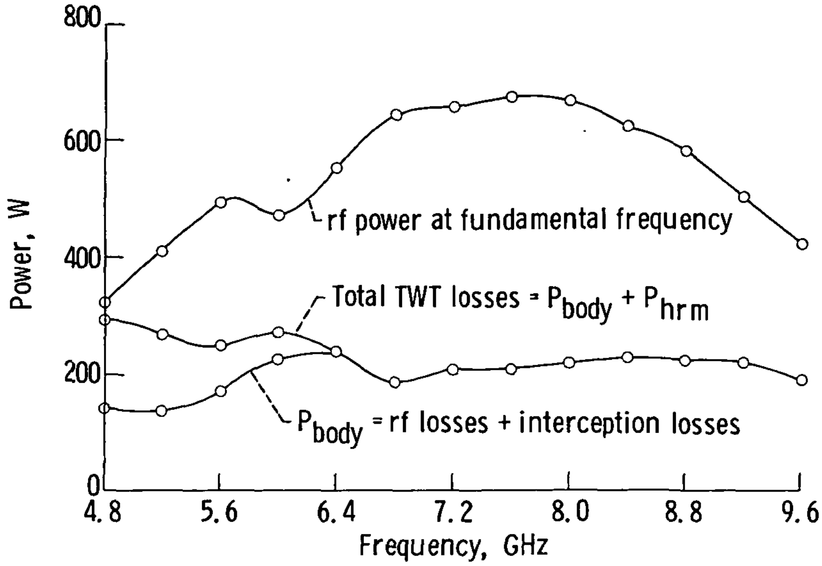
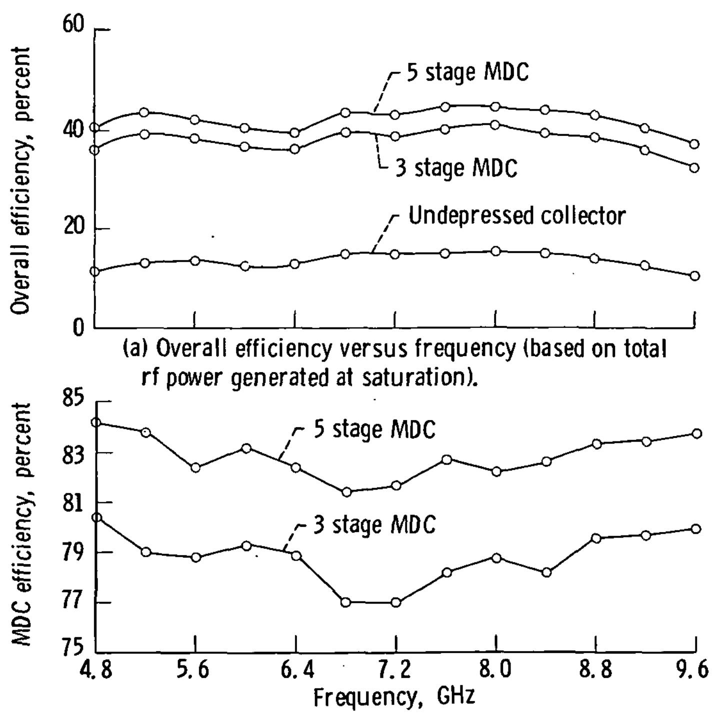


Figure 6. - Radiofrequency power and TWT losses versus frequency TWT 103 (at saturation).



(b) MDC efficiency versus frequency (at saturation).

Figure 7. - TWT 103 with MDC 1WX5.

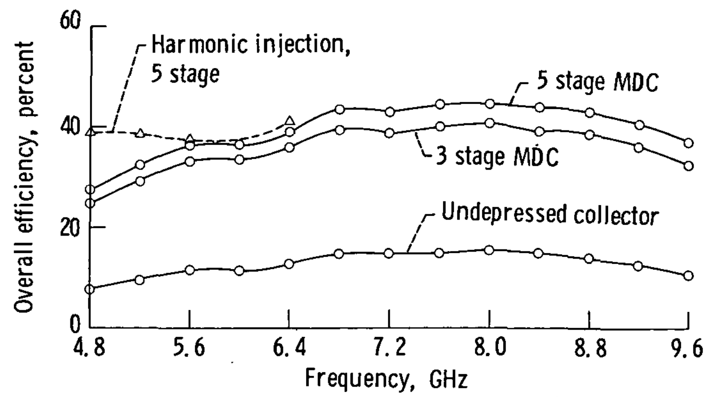
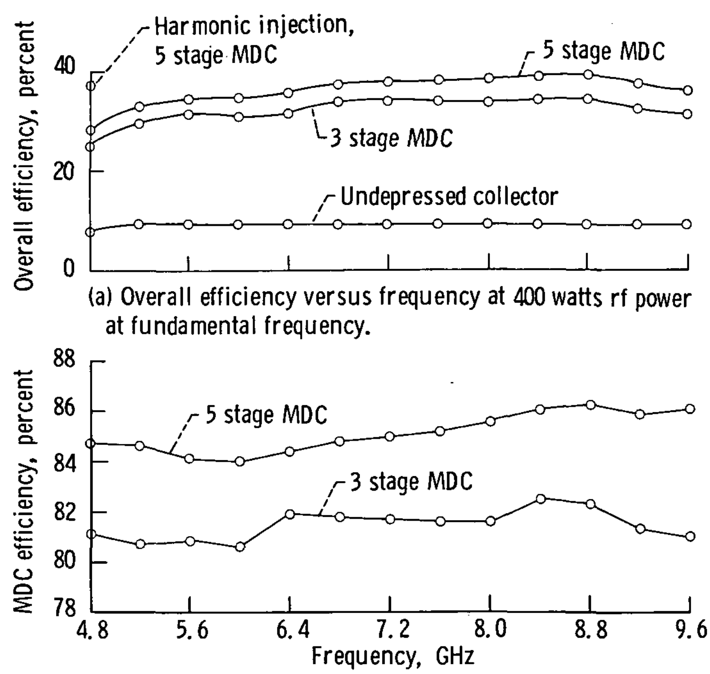


Figure 8. - Overall efficiency versus frequency (at saturation) (based on rf power at the fundamental frequency). TWT 103 with MDC 1WX5.



(a) Overall efficiency versus frequency at 400 watts rf power at fundamental frequency.

(b) MDC efficiency versus frequency at 400 watts rf power at fundamental frequency.

Figure 9. - TWT 103 with MDC 1WX5.

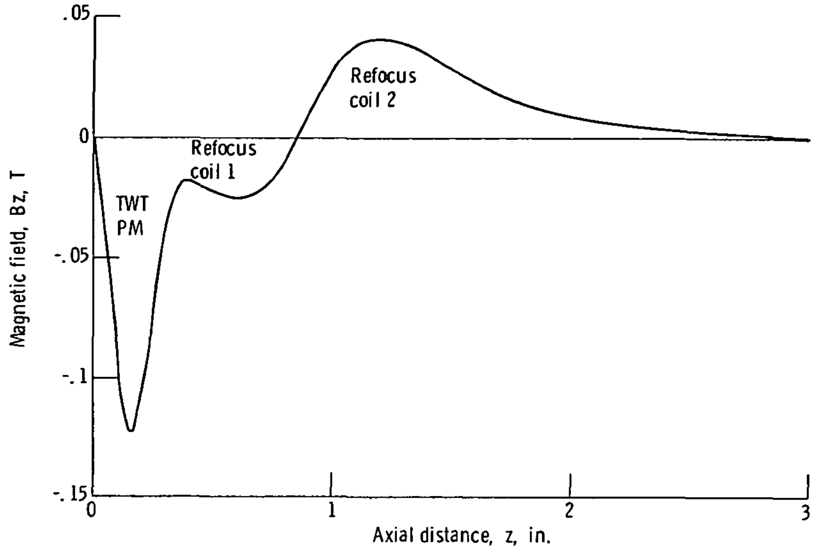


Figure 10. - Typical refocusing field profile.

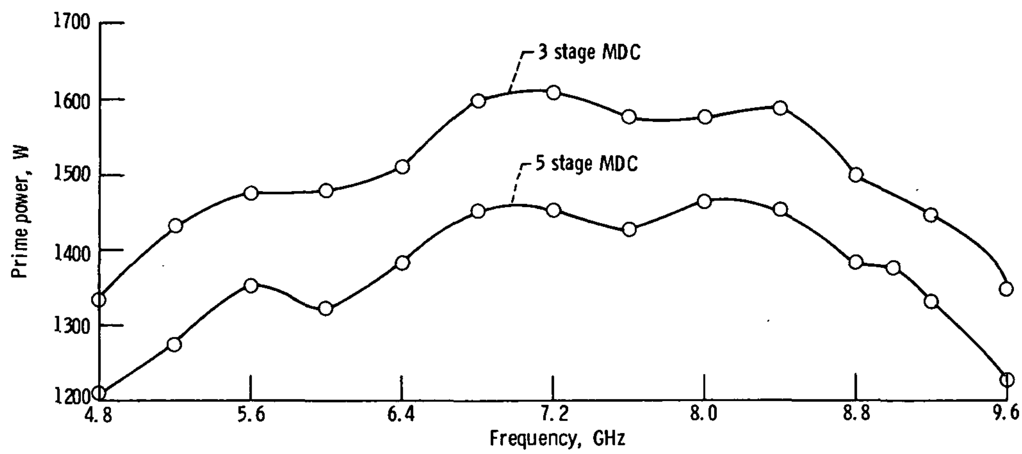


Figure 11. - Prime power required versus frequency (at saturation). TWT 103 with MDC 1WX5.

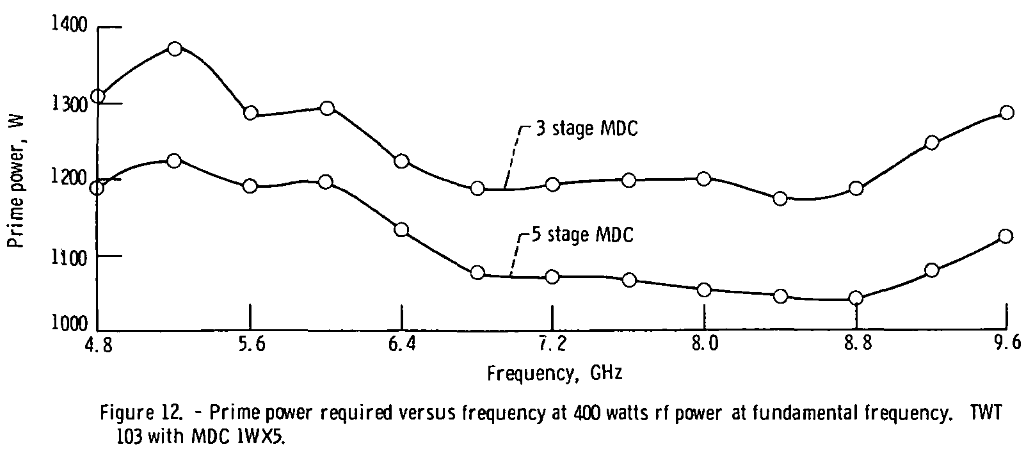
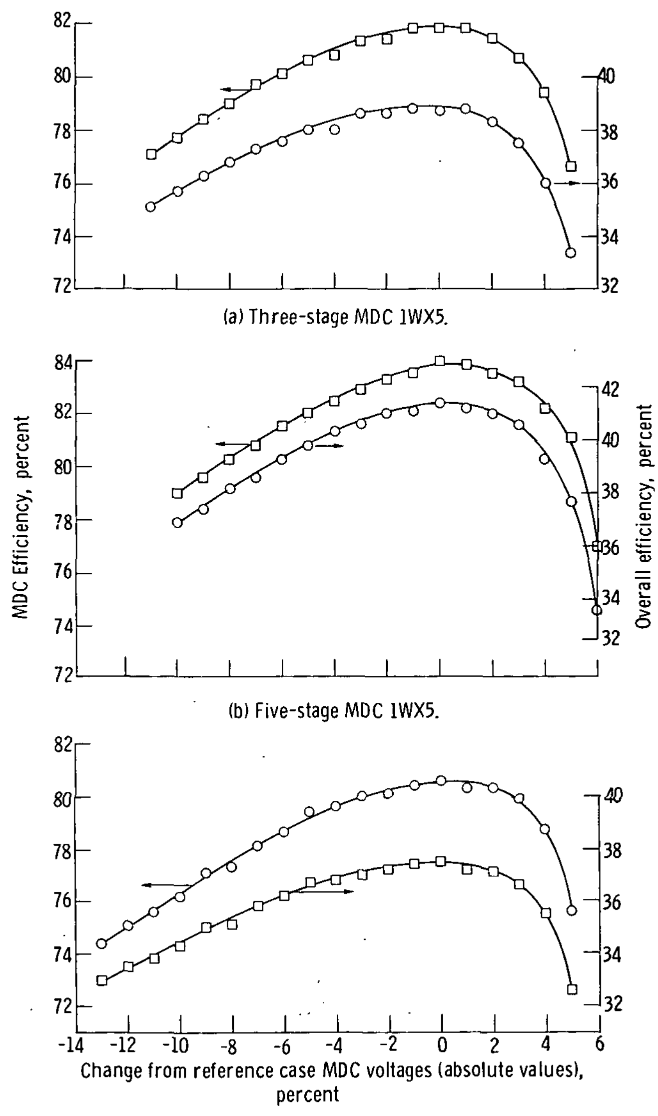


Figure 12. - Prime power required versus frequency at 400 watts rf power at fundamental frequency. TWT 103 with MDC 1WX5.



(c) Simplified three-stage MDC.

Figure 13. - Variation in MDC and overall efficiencies as functions of small changes in MDC voltages for TWT 101 (reference case: saturation at 8.4 GHz).

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16. Abstract

Small, three- and five-stage depressed collectors were evaluated in conjunction with a 4.8- to 9.6-GHz TWT of 325- to 675-W power output and a beam of 0.5 microperv. The multistage depressed collector (MDC) performed well even though its design had been optimized for a TWT of identical design but considerably less output power. Despite large, fixed losses (rf losses, interception losses, and harmonic power generated losses), significant efficiency enhancement was demonstrated with both the three- and five-stage depressed collectors. At saturated rf power output, the improvement in the overall efficiency ranged from a factor of 2.5 to 3.0 for the three-stage collector and a factor of 3.0 to 3.5 for the five-stage collector. At saturation three-stage collector efficiencies of 77 to 80 percent and five-stage collector efficiencies of 81 to 84 percent were obtained across the frequency band. An overall efficiency of 37.0 to 44.3 percent (average of 41.2 percent) across the frequency band of 4.8 to 9.6 GHz was demonstrated with the use of harmonic injection. For operation below saturation, even larger relative improvements in the overall TWT efficiency were demonstrated. Collector performance was relatively insensitive to the degree of regulation of the collector power supply.

17. Key Words (Suggested by Author(s))
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