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Naval Research Laboratory

Washington, DC 20375-5000

NRL Memorandum Report 6816

Depressed Collector Experiments on a Quasioptical Gyrotron

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**JAYCOR, Inc.*,
Vienna, VA

April 17, 1991

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** 1991 April 17	**3. REPORT TYPE AND DATES COVERED** Interim

4. TITLE AND SUBTITLE
Depressed Collector Experiments on a Quasioptical Gyrotron

5. FUNDING NUMBERS
J. O. #47-3046-0-1

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Washington, DC 20375-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL Memorandum Report 6816

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Department of Energy	ONR
Washington, DC 20545	Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*JAYCOR, Inc., Vienna, VA

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A simple, single-stage collector has been tested on the quasioptical gyrotron (QOG) experiment at the Naval Research Laboratory (NRL). This is the first application of a depressed collector to a high-power gyrotron, and was relatively easily accomplished due to the natural separation of the electron beam and the output radiation in the QOG. Collector efficiencies as high as 50% and overall efficiencies up to 16% were observed. The output power reached 431 kW with an overall efficiency of 13% and a collector efficiency of 41%. The collector efficiency was limited in this experiment due to interception of approximately 15% of the electron beam on an undepressed section of the beam guide, a problem readily correctable with a small change in the beam guide dimensions. If this part of the electron beam was collected at the collector potential, the overall and collector efficiencies would increase to 16% and 55% respectively. The maximum collector efficiency would increase to 58% (at high output power) and the best overall efficiency would increase to 20% (at lower output power).

14. SUBJECT TERMS

Quasioptical gyrotron	Collector
QOG	Depressed collector

15. NUMBER OF PAGES
16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

CONTENTS

DEPRESSED COLLECTOR EXPERIMENTS ON A QUASIOPTICAL GYROTRON

I. INTRODUCTION

There is currently a need for megawatt average power sources in the 100–300 GHz range for electron cyclotron heating (ECH) of fusion plasmas. For example, the Compact Ignition Tokamak (CIT) design[1] includes 30 MW of 280 GHz radiation and the International Thermonuclear Experimental Reactor (ITER) design[2] requires 20 MW of 120 GHz rf power. The leading candidate for such a source is the waveguide cavity gyrotron,[3] having produced an output power of 940 kW at an efficiency of 35% and a frequency of 140 GHz,[4] and 1.2 MW at an efficiency of 20% at 148 GHz[5] in a continuous-wave (CW) relevant configuration. Due to the large fraction of energy remaining in the electron beam after the interaction (65–80%), the addition of a depressed collector could significantly increase the overall efficiency and reduce the amount of collector cooling needed. However, a difficult problem to overcome is the separation of the rf power from the electron beam, necessary in most depressed collector designs. This separation occurs naturally in the quasioptical gyrotron (QOG),[6, 7] shown in Fig. 1, making the implementation of a depressed collector relatively straightforward in the QOG. A single-stage depressed collector has been tested on the QOG experiment at the Naval Research Laboratory (NRL), representing the first application of a depressed collector to a high-power gyrotron. One advantage of the single-stage depressed collector over multi-stage depressed collectors is the simplicity of design and implementation. A more important advantage may be that secondary electron emission in the collector should be no more important in the single-stage depressed collector than in an undepressed collector. This is due to the fact that the electron beam may be collected far inside the depressed collector where the electric field may be negligibly small. Conversely, current multi-stage depressed collector designs have relatively large electric fields in the collector due to size limitations, and care must be taken to avoid secondary electrons being accelerated toward the resonator.

Overall efficiencies as high as 16% were measured in the experiment described here, and were limited by the fact that approximately 15% of the current was collected before it reached the depressed collector. This problem could be easily corrected by simply increasing the dimensions of the electron beam transport system which would result in peak overall efficiencies of 20%, assuming that all of the electrons could be collected at the potential of the depressed collector. At the highest output powers measured (431 kW) the measured overall efficiency of 13% would rise to 16% with a properly designed electron beam transport system. The peak measured collector efficiency, the efficiency of recovering energy from the electron beam leaving the resonator, was greater than 50%, but could only be obtained at the expense of lower overall efficiency. The collector efficiency was 41% at the highest output power, and would rise to 55% if all of the electron beam were collected at the collector potential.

The configuration of the NRL QOG experiment with depressed collector is described in Section II. Results of the experiments are presented in Section III and analyzed and discussed in Section IV. A brief summary of the results and conclusions is presented in Section V.

Manuscript approved February 28, 1991.

II. DESCRIPTION OF EXPERIMENT

A QOG experiment designed to produce 0.5 MW of rf radiation at a frequency of 120 GHz has been assembled at NRL. A brief description of the experiment is presented here, with the design equations[8] and a more detailed experiment description[9] presented elsewhere. A schematic diagram of the experiment is shown in Fig. 1. The gyrating electron beam is generated by a magnetron injection gun located below and in the fringing magnetic field of the superconducting magnet. The beam propagates up through the drift tube, across the open resonator, through the uptaper, and is finally absorbed in the collector, located above the magnet dewar. A low-field trim coil is located just below the collector to prevent the beam electrons from expanding too rapidly and being collected prior to reaching the collector. The microwave fields interact with the electron beam in the open region between the drift tube and the tip of the uptaper. The microwave power diffracted around each mirror is collected as output and propagated through thin mylar windows out of the vacuum enclosure. Typical parameters of the experiment are given in Table I.

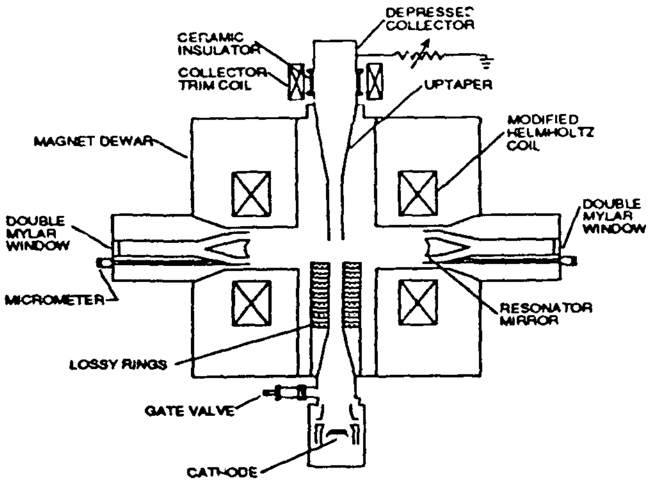

Figure 1: Schematic diagram of the NRL QOG experiment.

The Varian VUW-8144 electron gun[10] used in this experiment was originally designed for use in the MIT megawatt gyrotron program.[11] Due to the relative insensitivity of the QOG to the electron beam radius, the emitter could be placed in the magnetic field necessary for high perpendicular to parallel velocity ratios (α) in the resonator. Simulation of the beam electrons was accomplished using a standard trajectory-tracing code,[12] which indicated that achievable values of average α ranged from 1.8 with a spread (standard deviation in α) of 13% at low currents to 1.3 with a spread of 23% at 50 A. The simulations indicated that reasonable gun performance could be obtained with the emitter placed in a magnetic field yielding a compression ratio of 24. In this position, the beam in the cavity had a mean radius of 0.56 cm and a thickness of 0.05 cm.

The use of an annular electron beam means that different electrons experience different peak electric fields as they pass through the resonator, so that not all of the electrons experience the electric field necessary for optimum efficiency. The nonlinear efficiency is

Table I: Typical parameters of the NRL QOG experiment.

Frequency (f)	120 GHz
Electron Energy	112 keV
Electron Current	50 A
Mirror Diameter ($2a$)	4.5 cm
Radius of Curvature (R_c)	38.7 cm
Mirror Separation (d)	21.2 cm
Longitudinal Mode Spacing ($\Delta f/f$)	0.59%
Radiation Waist Radius (w_o)	1.17 cm
Electron Beam Radius	5.6 mm
Electron Beam Thickness	0.5 mm
Normalized Interaction Length (μ)	12
Output Coupling (T, round trip)	3.1%
Diffraction Quality Factor (Q_d)	34,850
Ohmic Quality Factor (Q_o)	438,000
Total Quality Factor (Q)	32,280
Normalized Electric Field (F)	0.13
Output Power	430 kW
Peak Ohmic Heating Density	5.4 kW/cm^2
Total Ohmic Power (per mirror)	15.6 kW
Number of Interacting Modes	~7

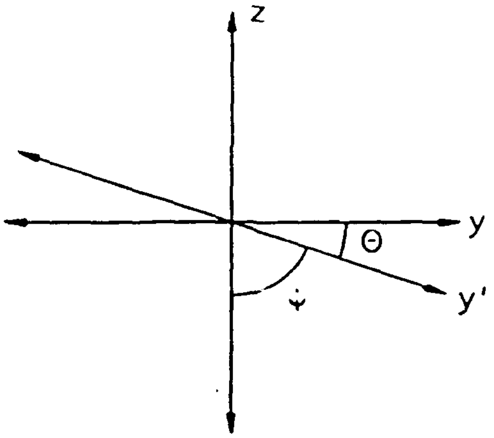

Figure 2: Orientation of the resonator and electron beam axes.

degraded by a factor of approximately 1/3 when compared to the efficiency of a device using a pencil beam.[13] As an attempt to minimize this effect, the resonator axis was tilted by 2° with respect to the plane perpendicular to the electron beam axis, as indicated in Fig. 2. Recent theory[14] indicates that this allows each of the beam electrons to interact more efficiently with the resonator fields, enlarging the parameter space for stable, single-mode operation. The effectiveness of this modification will be reported in the future.

The electron gun has been operated at voltages up to 110 kV and currents up to 65 A. With the magnetic field and cathode voltage fixed, the beam α could be varied by changing the voltage applied to the intermediate anode of the gun. The ratio of intermediate anode voltage to cathode voltage ($V_{\text{int}}/V_{\text{cat}}$) was set by a voltage divider and varied in the experiment from 0.63 to 0.68. At low ratios, corresponding to large electric fields at the cathode, gun simulations predicted total reflection of the electron beam. Experimentally, the beam did propagate, however, the current diagnostics for the collector, drift tube, uptaper, and intermediate anode became very noisy. To understand this anomaly, one must understand the differences between the gun simulations and the experiment. The simulations assume a steady state, with the gun voltages already applied and the current at the final value. In the experiment, the electron gun voltages are pulsed on, with a risetime of approximately 4 μsec. The electron beam current risetime is somewhat faster, approximately 2 μsec, due to the emission being temperature limited. As the electron gun voltage is pulsed on, both the intermediate anode and the cathode voltage rise with their ratio remaining constant. At lower voltages, the current is predicted by the simulations to propagate, reflecting only when the voltage rises above a threshold value. It is possible that some of the electrons are reflected back toward the electron gun during the rise of the voltage pulse, creating a charge density great enough to shield out some portion of the intermediate anode voltage at the cathode. If the electric field at the cathode is depressed enough, the transverse velocity will be reduced ($v_\perp \propto E_{\text{cathode}}/B_{\text{cathode}}$) to the point that reflection does not occur and the electron beam will again be able to propagate to the resonator. The large noise associated with this phenomenon may be due to the space charge cloud and associated instabilities.

A simple, single-stage depressed collector has been added to the experiment. This is the first application of a depressed collector to a high-power gyrotron. The implementation was relatively easily accomplished due to the natural separation of the electron beam from the rf radiation. As shown in Fig. 1, the collector was depressed by inserting a resistance between the collector and ground. The values of the resistance used in the experiment were 1.15, 1.3, and 1.96 kΩ, making the collector voltage dependent on the collector current.

III. EXPERIMENTAL RESULTS

The QOG was run under widely varied conditions obtained by separately adjusting the electron gun's intermediate anode voltage, the cathode voltage and the current. The magnetic field was kept at a constant 4.7 T, tapering from 1% higher, 2.4 cm closer to the electron gun to 1% lower, 2.4 cm closer to the collector. The resonator mirror separation was 21.2 cm, corresponding to a longitudinal mode separation of 707 MHz. The number of interacting modes ($N_{\text{modes}} \approx \beta_{\|} d/w_o$) for this configuration is about 7. The output frequency was near 120 GHz, but varied with beam energy and current. Attempts were made to separately maximize the uncorrected efficiency, the collector efficiency, and the output power by varying the electron beam voltage, current, and alpha (accomplished by varying the electron gun's intermediate anode voltage). The voltage divider used to set the ratio between the intermediate anode and cathode voltages was changed only a few times, with most of the data presented here having been taken with a common voltage division of 68% (i.e. $V_{\text{int}} = 0.68 V_{\text{cathode}}$).

Data was obtained at currents up to 50 A, however, due to having only three available depression resistors, operation was not optimized at all values of electron gun voltage and current. A further complication arises from the fact that approximately 15% of the beam current is collected on the uptaper before reaching the collector. This part of the current is not depressed when it is collected, a fact that is accounted for in the results presented here. Thus, the overall efficiency with the depressed collector is calculated as

$$\eta = P_{\text{out}} / \left\{ V_{\text{beam}} \left(I_{\text{cathode}} - I_{\text{collector}} \right) + \left(V_{\text{beam}} - R_{\text{collector}} I_{\text{collector}} \right) I_{\text{collector}} \right\} \tag{1}$$

where P_{out} is the peak output power, V_{beam} is the electron gun cathode voltage, and I_{cathode} and $I_{\text{collector}}$ are the cathode and collector currents. The average output power is measured by a laser calorimeter coated with additional paint to make it absorb 95% of the power incident on it at 120 GHz. The peak output power is calculated by dividing the average power by the rf pulse width (measured by a diode detector) and the repetition rate. The overall efficiency with the depressed collector is plotted in Fig. 3 along with the uncorrected efficiency ($\eta_{\text{uncorrected}} = P_{\text{out}} / (V_{\text{beam}} I_{\text{cathode}})$), and the corresponding output powers are plotted in Fig. 4.

The efficiency with which the depressed collector recovers energy remaining in the electron beam as it emerges from the resonator is defined as[15]

$$\eta_{\text{collector}} = \frac{1 - \eta_{\text{uncorrected}} / \eta}{1 - \eta_{\text{uncorrected}}} , \tag{2}$$

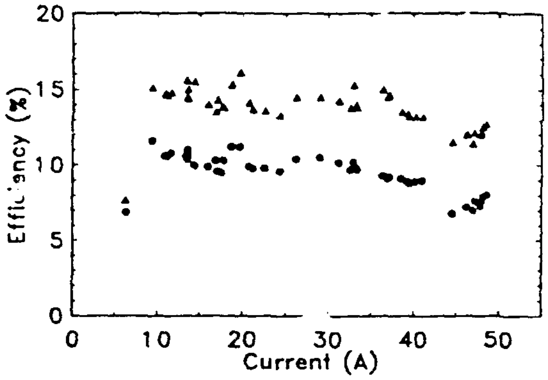

Figure 3: The output efficiency (η) of the QOG with a depressed collector (triangles) and the efficiency without accounting for the collector depression ($\eta_{\text{uncorrected}}$, circles).

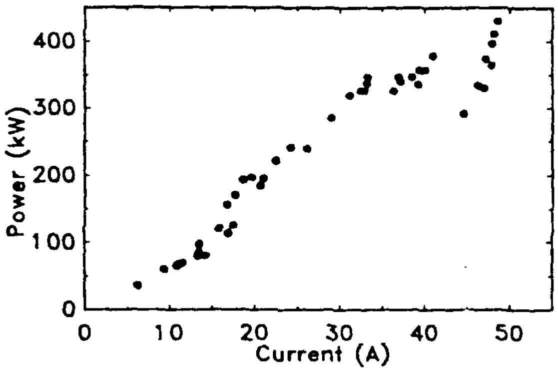

Figure 4: Output power as a function of current for the data shown in Fig. 3.

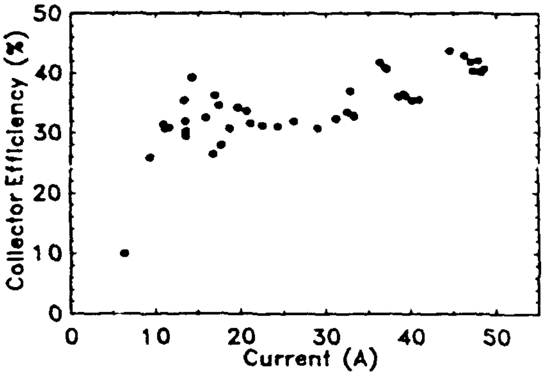

Figure 5: Efficiency of energy extraction from the spent electron beam ($\eta_{\text{collector}}$) as a function of current for the data shown in Fig. 3.

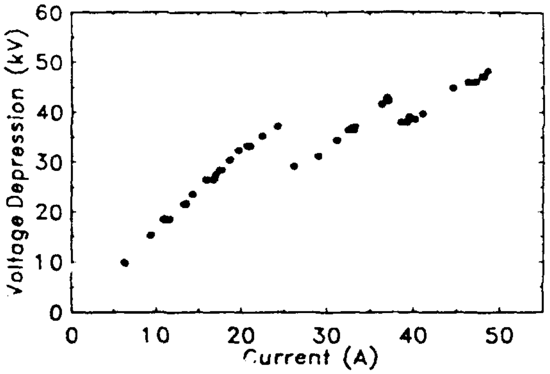

Figure 6: The negative of the collector voltage for the data shown in Fig. 3.

and is plotted in Fig. 5 for the data shown in Fig. 3. Attempts were made to raise the collector efficiency by increasing the voltage depression of the collector; however, above a certain voltage, the electronic efficiency degraded rapidly. This was accompanied by electron current being collected by the intermediate anode, presumably either from electrons being electrostatically reflected by the collector potential or from secondary electrons being produced in the collector and accelerated back toward the electron gun. In our current experiment we have no way to differentiate between these two sources of electron current, however, secondary electron acceleration in the collector is not expected since the electric field at the point of electron collection is essentially zero. This is due to the entire collector structure being at a single potential with the electrons being collected approximately one collector diameter inside the collector. The electron deceleration is accomplished as the electrons enter the collector structure rather than as they contact the collector surface. Additionally, the space charge in the electron beam itself generates an electric field that accelerates any secondary electrons created back into the collector.

The negative of the collector voltage ($I_{\text{collector}} R_{\text{collector}}$) for the data in Fig. 3 is plotted in Fig. 6. At high collector voltage values, the depression was limited by breakdown in the air between the collector and the collector trim coil housing. This limit of approximately 50 kV was not a serious limit on overall efficiency except at the highest voltage operation, which occurred at the highest electron beam currents. In general, higher values of collector depression than the local maxima shown in Fig. 6 decreased the overall efficiency by decreasing the electronic efficiency contribution faster than the collector efficiency contribution increased.

IV. DISCUSSION

As can be seen in Fig. 4, an output power of 431 kW was reached at a current of 50 A. The electron gun voltage was 112 kV and 8 of the 50 A of emitted current were collected on the uptaper (i.e. not collected at the depressed voltage). This led to an overall efficiency of 13% and a collector efficiency of 41%. This collector efficiency may be compared to that of a multi-electrode collector designed specifically for the NRL QOG (subject to somewhat severe space limitations) of 63%.[16] Similar calculations have been

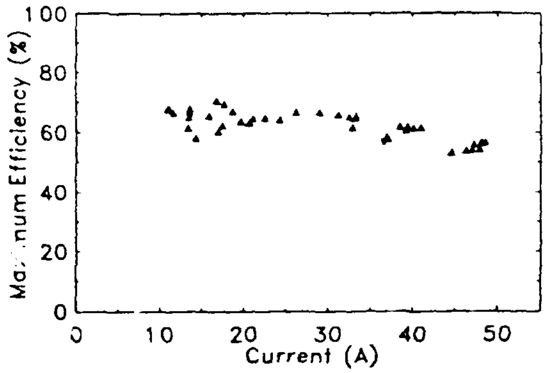

Figure 7: A lower bound on the efficiency of the electrons in the beam that interact most efficiently with the resonator fields.

performed for a gyroklystron predicting a collector efficiency of 76%.[17]

A collector efficiency of 49% was measured with a gun voltage of 98 kV and a current of 34 A. The output power was 222 kW at an overall efficiency of 13%. Collector efficiencies in excess of 50% were measured, but could only be achieved at the expense of lower overall efficiencies. The best overall efficiency was 16% at a gun voltage of 89 kV and a current of 20 A. The output power was 197 kW and the collector efficiency was 34%.

The electron dynamics in the presence of the depressed collector may be understood as follows. To within a few percent, all of the electron's energy is converted into motion parallel to the magnetic field between the resonator and the collector by the adiabatically decreasing magnetic field. Therefore, the collector may be depressed to a voltage approximately equal to the energy of the least energetic of the beam electrons divided by e. Since each of the beam electrons have essentially the same energy as they leave the electron gun, the electrons with the lowest energies as they enter the collector are those which have interacted most efficiently in the resonator. Thus, the magnitude that the collector can be depressed is set by the interaction efficiency of the most efficient electrons in the beam. Assuming that the collector is depressed by the maximum amount for each data point shown in Fig. 3 (although it most probably is not), the efficiency of the most efficient electrons may be easily calculated. This calculated efficiency, which falls in the range of 60-70% for most of the data as shown in Fig. 7, is a lower bound since it is possible that the collector could have been depressed further. However, at least some of the points are optimized and most of the data nearly is. Assuming that these most efficient electrons lose all of their velocity perpendicular to the magnetic field in the resonator yields a lower bound on the alpha of these electrons. The minimum alpha values of the most efficient electrons are plotted in Fig. 8.

Approximately 15% of the electron beam in the experiment is collected on the uptaper which is not depressed (i.e. it remains at ground potential). There is no reason to expect that this part of the beam is different in any way (other than its slightly larger radius) than the rest of the electron beam since the beam in the resonator is approximately 4 radiation wavelengths in diameter with a thickness of about 0.2 wavelengths. Therefore, it is reasonable to expect that the entire beam could be collected at the potential of the

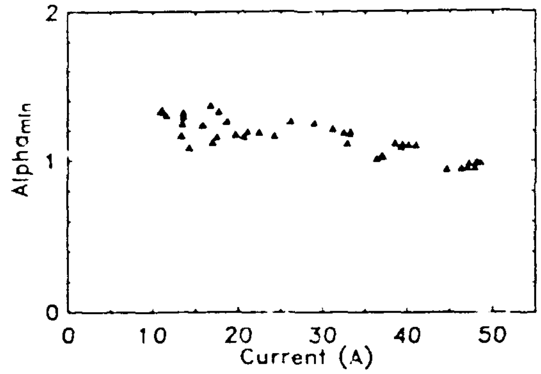

Figure 8: A lower bound of the alpha values of the beam electrons that interact most efficiently in the resonator.

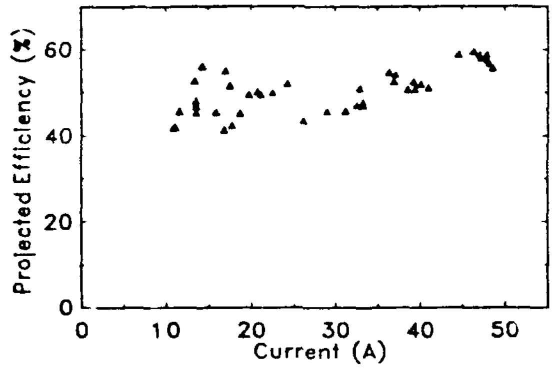

Figure 9: The projected collector efficiency assuming that the part of the electron beam collected on the uptaper was actually collected at the collector potential.

depressed collector by simply enlarging the uptaper enough to allow the electron beam to propagate to the collector. With this assumption, the projected collector and overall efficiencies are significantly increased, as can be seen in Fig. 9 and Fig. 10. As can be seen from the figures, peak efficiencies in excess of 20% are achieved at low power, with the efficiency remaining at approximately 16% at the highest powers. Corresponding collector efficiencies at the highest output powers are above 55-58%.

V. CONCLUSIONS

We have tested a simple, single-stage depressed collector on the NRL QOG; the first demonstration of a depressed collector on a high power gyrotron. Due to the discrete resistance values available for the collector depression and the fact that approximately 15% of the current was not depressed, the collector efficiency could not be optimized at each value of electron gun voltage and current. Even so, collector efficiencies in excess of 50% were measured, compared to a value of 76% predicted for an optimized multi-electrode collector for a gyroklystron. Total output efficiencies in excess of 16% were measured with the efficiency remaining high (13%) at the highest output powers (431 kW). Assuming that all of the beam electrons could be collected at the collector potential, the collector efficiency

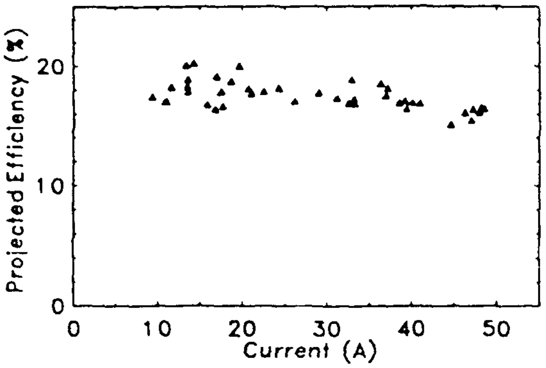

Figure 10: The projected total efficiency assuming that the part of the electron beam collected on the uptaper was actually collected at the collector potential.

would rise to 55-58% at the highest output powers. This compares favorably with optimized multi-stage depressed collectors and may indicate the difficulty of achieving energy sorting in gyrotron depressed collectors. The total efficiency would rise to approximately 16% at this power and above 20% at lower power.

ACKNOWLEDGEMENTS

We thank Drs. Wallace Manheimer, Steven Gold and Robert McCowan for their many helpful discussions. This work was supported by the Office of Fusion Energy of the U.S. Department of Energy and by the Office of Naval Research.

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