

OPERATION OF A LOW-VOLTAGE HIGH-TRANSCONDUCTANCE FILED EMITTER ARRAY TWT (BRIEFING CHARTS)

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CONFERENCE BRIEFING CHARTS

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Operation of a Low-Voltage High-Transconductance Field Emitter Array TWT

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Introduction

- Implementation of “cold cathodes” as an electron source for RF vacuum devices can have a significant impact on many aspects of device operation

Cold Cathode Impact on RF Device Operation

- | | |
|----------------------------------|---|
| • No Cathode Wearout Mechanism | • Multi-Mode Operation |
| • Room Temperature Operation | • Infinite ON/OFF Isolation |
| • Eliminate Heater Power | • Device Miniaturization [†] |
| • High Current Density Operation | • Increased Interaction Efficiency [†] |
| • Instant Turn-on | • Improved Linearity [†] |
| • Eliminate HV Modulator | • Decreased Harmonic Power [†] |

[†]RF modulated cathode



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Introduction

Cold Cathode TWT History

- NEC Corporation
 - Late 1990s
 - Replaced thermionic cathode in X-Band TWT with Spindt-type cold cathode
 - 58 mA, 27.5 W, 10.5 GHz, 3% duty max (limited by TWT vacuum)
 - Focusing difficulties in first prototype – subsequently resolved
 - No recent activity
- Northrop Grumman Corporation
 - 1999 – 2002
 - C-Band cold cathode TWT
 - Single pulse up to 91 mA, 55 W, 4.5 GHz
 - 1% maximum duty factor at lower currents
 - 2002
 - RF-modulated cold cathode TWT
 - 5mA, 280mW, 6.75 GHz
 - No recent activity
- L-3 Communications – Electron Devices
 - 2007
 - C-Band cold cathode TWT
 - 30 mA, 18 W, 4.1 GHz, 1% duty
 - 10% duty at 10mA
 - 6 hrs lifetest at 1% duty, 2 hrs lifetest at 10% duty

Introduction



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L-3 Electron Devices Cold Cathode TWT Program

- Field emitter arrays have undergone a significant evolution in past several years, substantially reducing required operating voltages and potentially increasing life and reliability
- L-3 EDD has established a Vacuum Microelectronics Laboratory for testing of Cold Cathode Vacuum Devices
- A Field Emitter Array TWT test vehicle has been designed, fabricated and tested to evaluate the characteristics of the new low-voltage FEA cathodes and to characterize/optimize FEA TWT performance



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Introduction

- Progress To Date
 - Built laboratory, integrated equipment and control system
 - Designed and fabricated electron gun capable of controlling high current density FEA electron beam
 - Integrated FEA cathode into TWT electron gun
 - Designed and fabricated TWT circuit/magnetics for
 - excellent beam control
 - high efficiency
 - wide bandwidth
 - moderate gain
 - Built prototype cold cathode TWT
 - Demonstrated performance exceeding all past measures of performance including beam current, cathode current density, total run time, duty factor, RF peak power, RF average power
 - Performed life tests, cold cathode processing in TWT environment, noise measurements

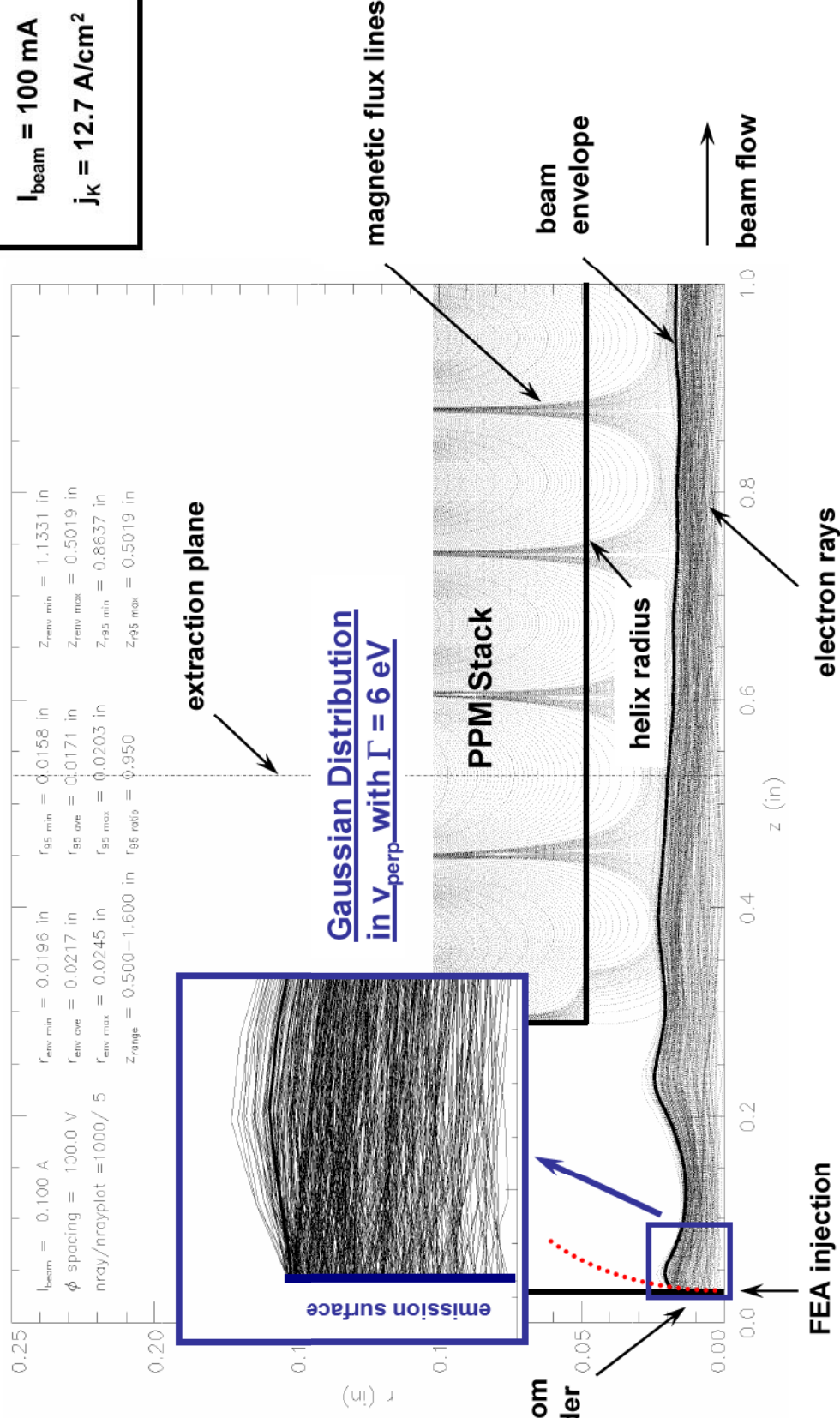
Simulation



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Electron Optics



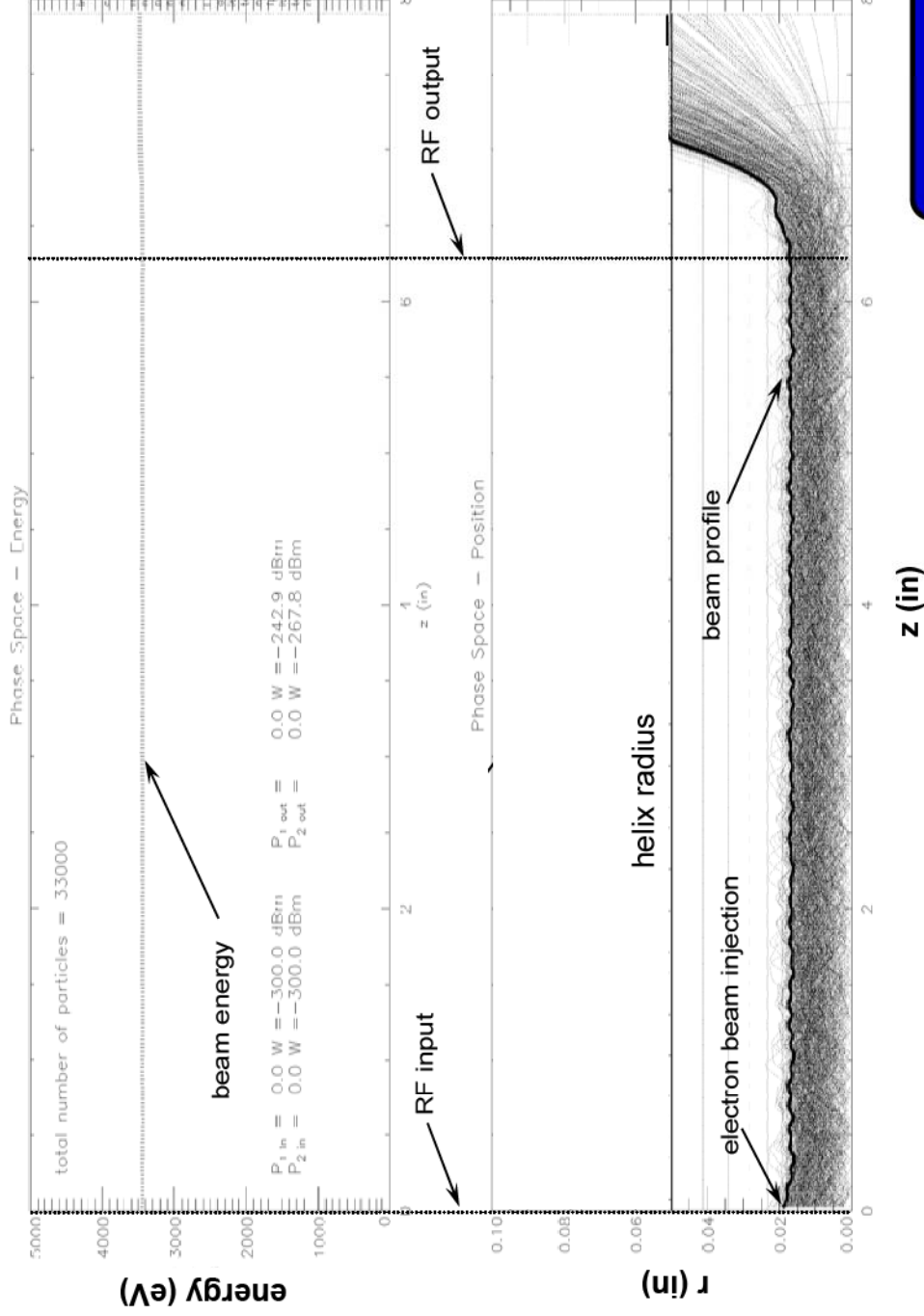
Simulation



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CHRISTINE3D Interaction Simulation – No RF Drive



$N_{\text{particles}} = 33000$

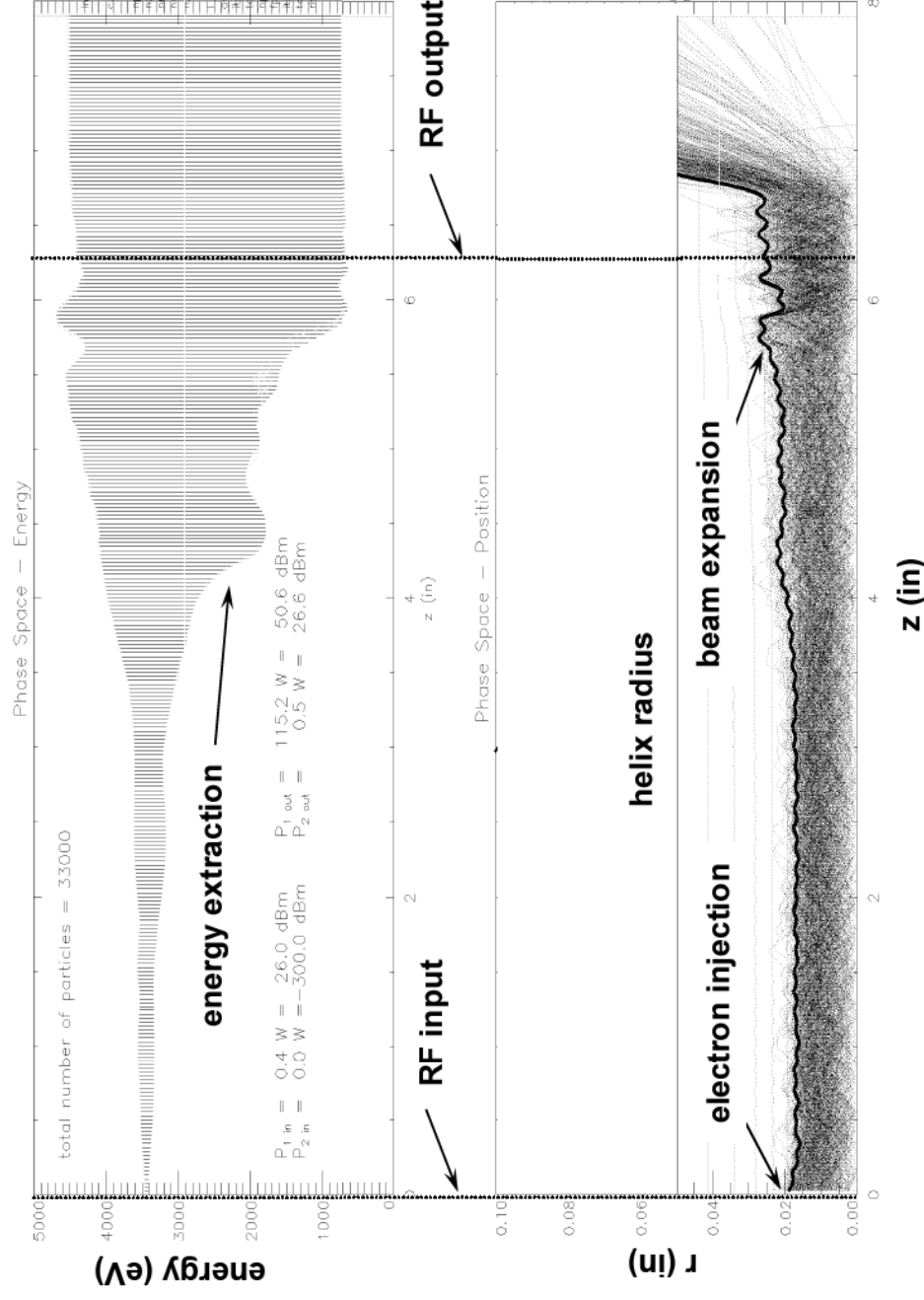
Simulation



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CHRISTINE3D Interaction Simulation – Saturated, Band Center

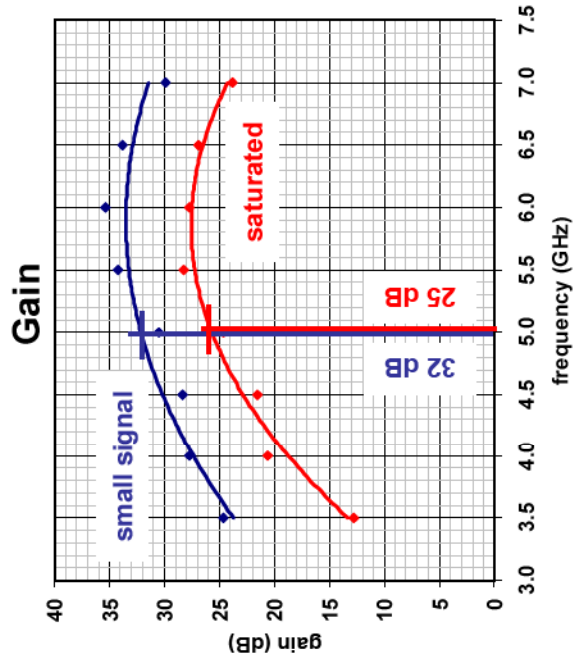
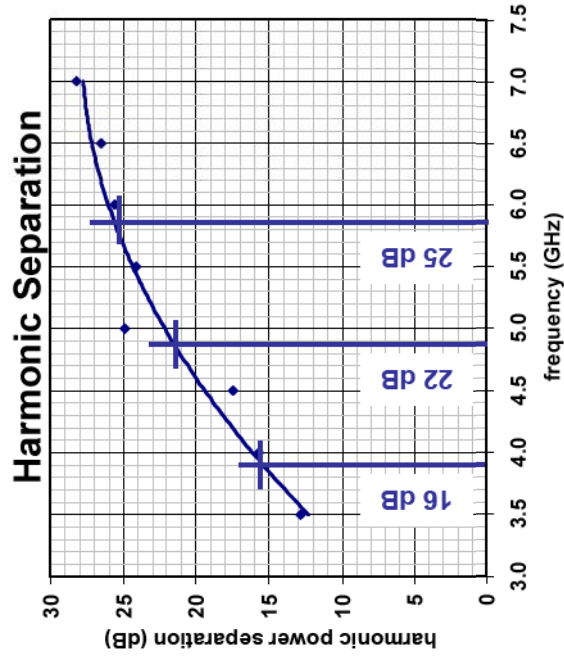
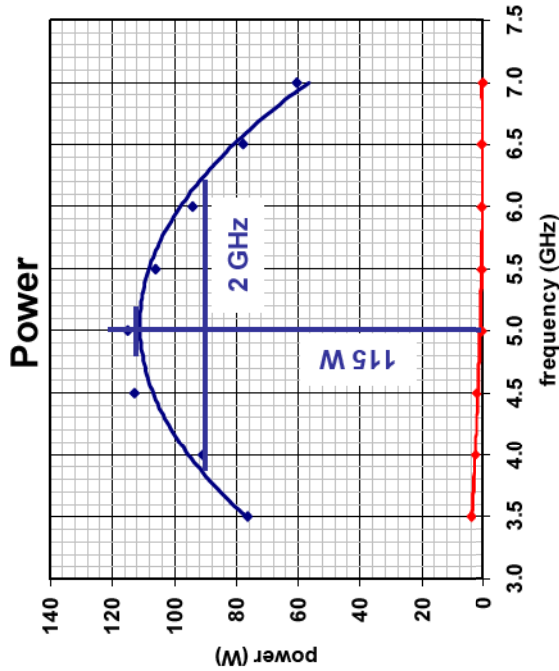


$P_{\text{RF}} = 115\text{W}$

Simulation



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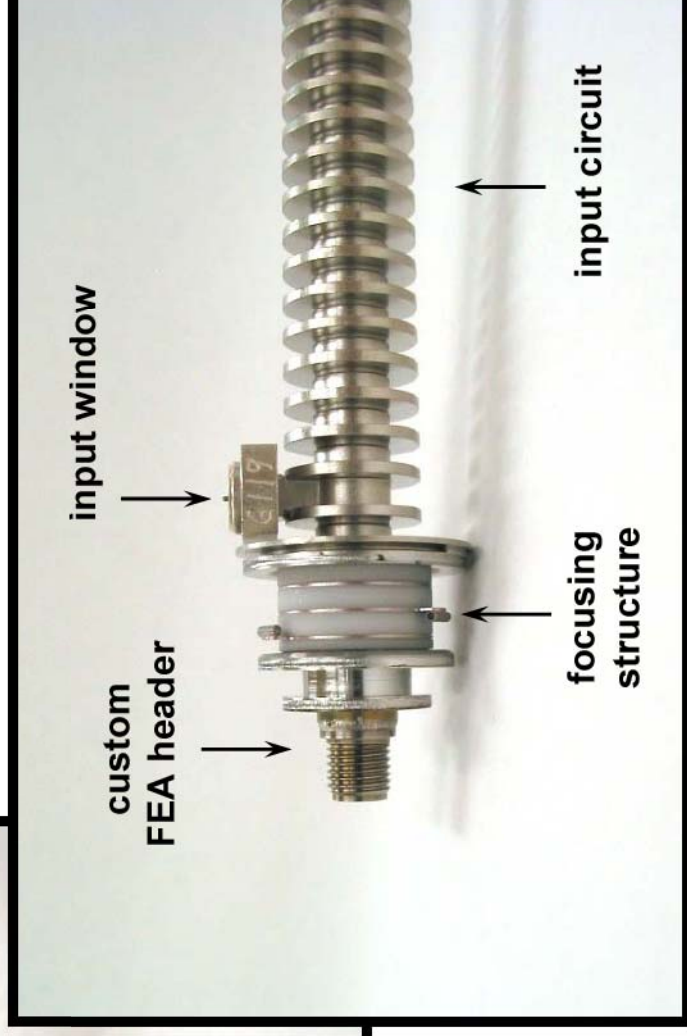
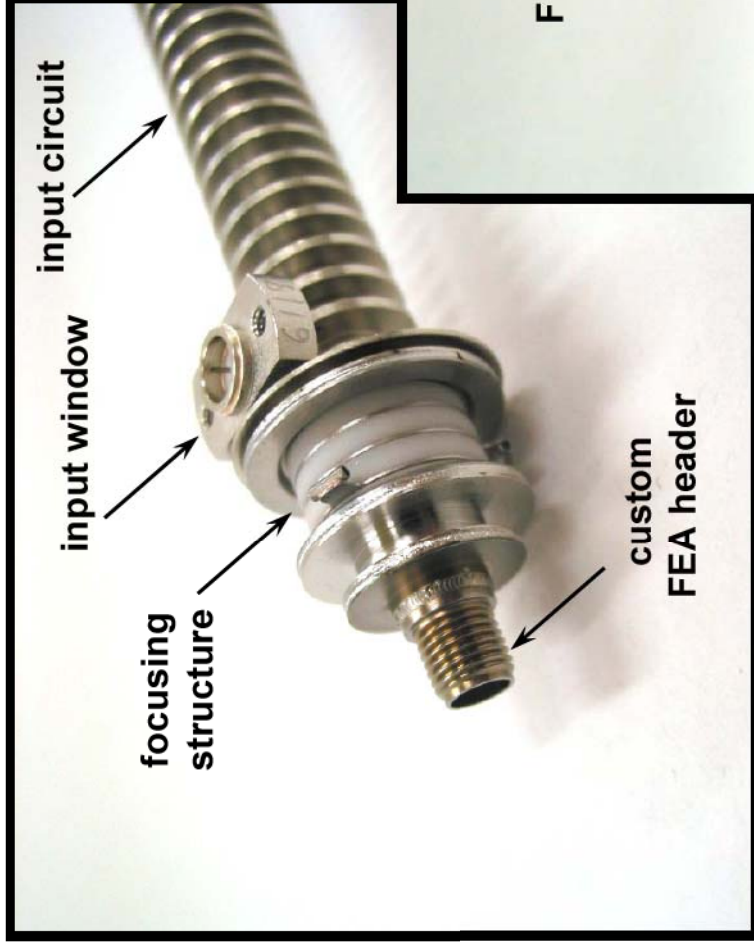
I_{beam}	100 mA
V_{beam}	3500 V
Sat Power	115 W
SS Gain	32 dB
Sat Gain	25 dB
η_{circuit}	32 %
1 dB B/W	2 GHz
3 dB B/W	4 GHz



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Hardware

Prototype #1 – Pre-Exhaust

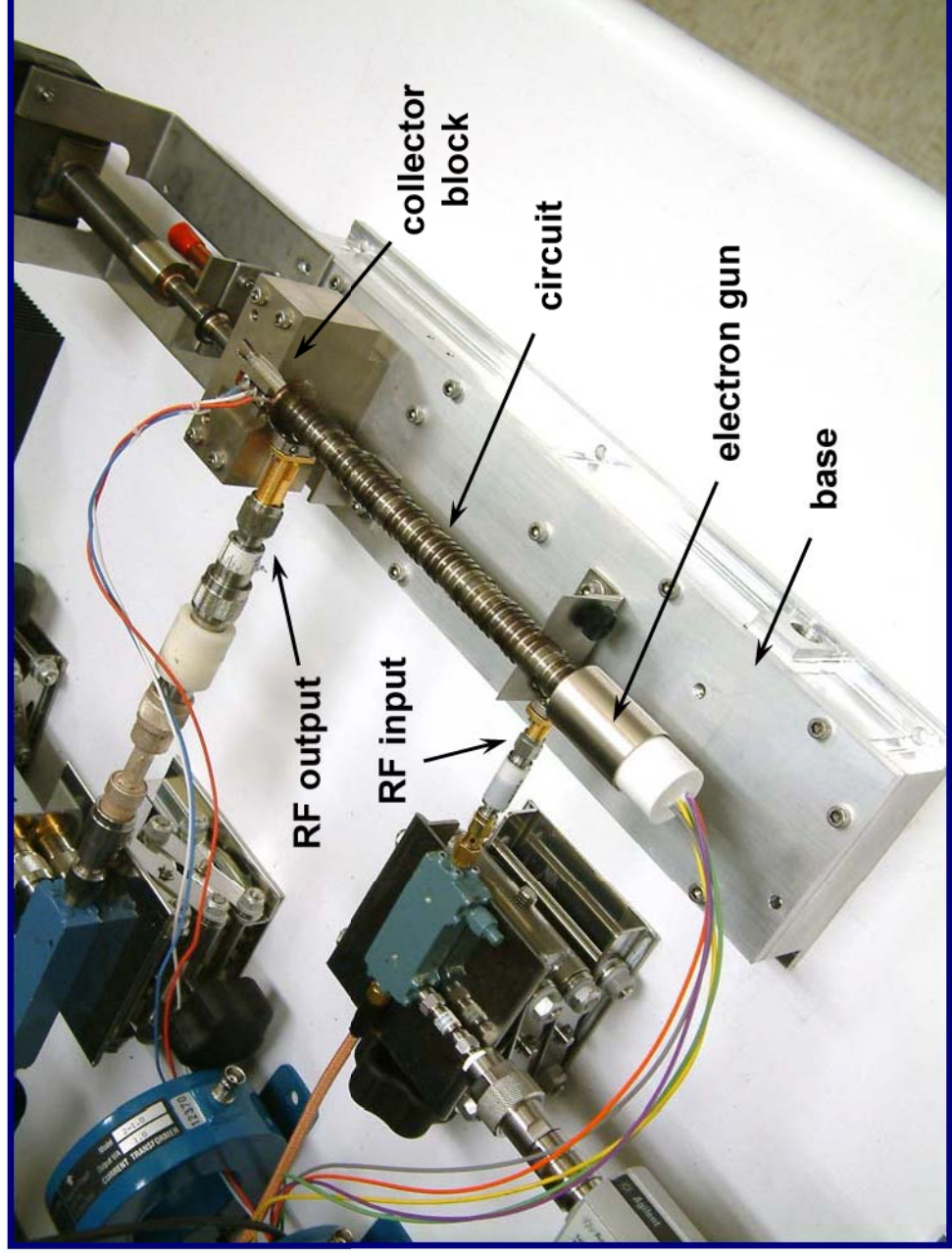


Hardware



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Final Experimental Configuration – Prototype #1



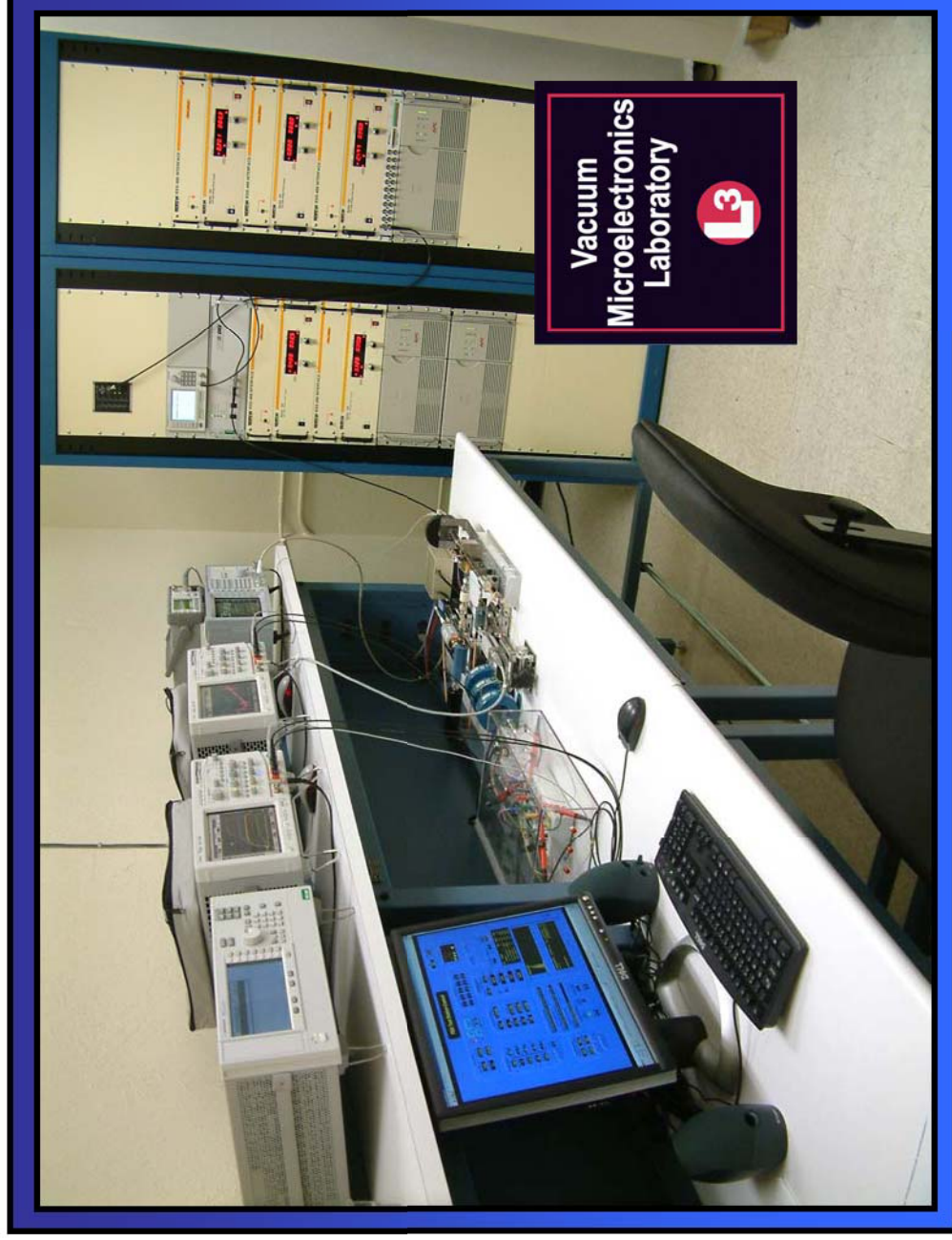
SRI Emitter Characteristics

diameter	1 mm
tip number	50,000
tip material	Molybdenum
a_{FN}	0.030 AV^2
b_{FN}	490 V

Laboratory



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Vacuum Microelectronics Laboratory

- Established for Test of Cold Cathode RF Vacuum Devices
- Dedicated Equipment
- Fully Functional
- Computer Controlled
- Life Test System Operational

Experimental Results



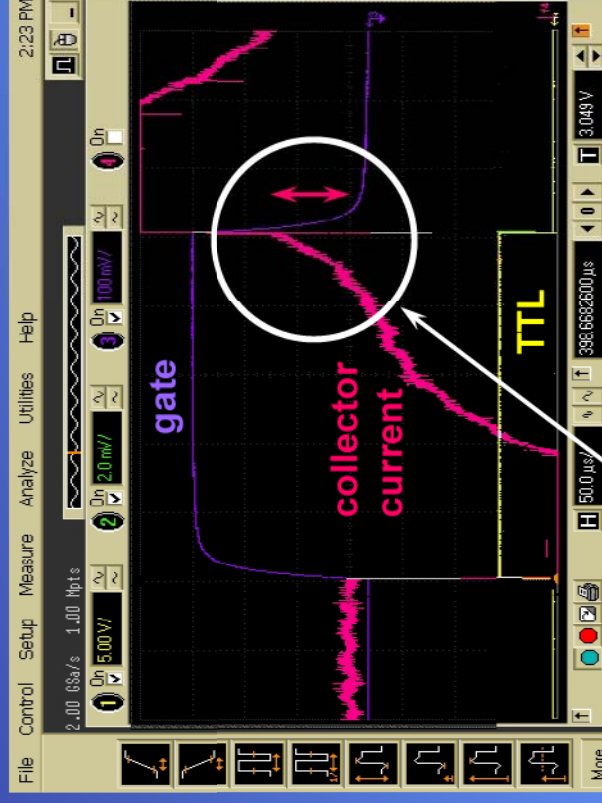
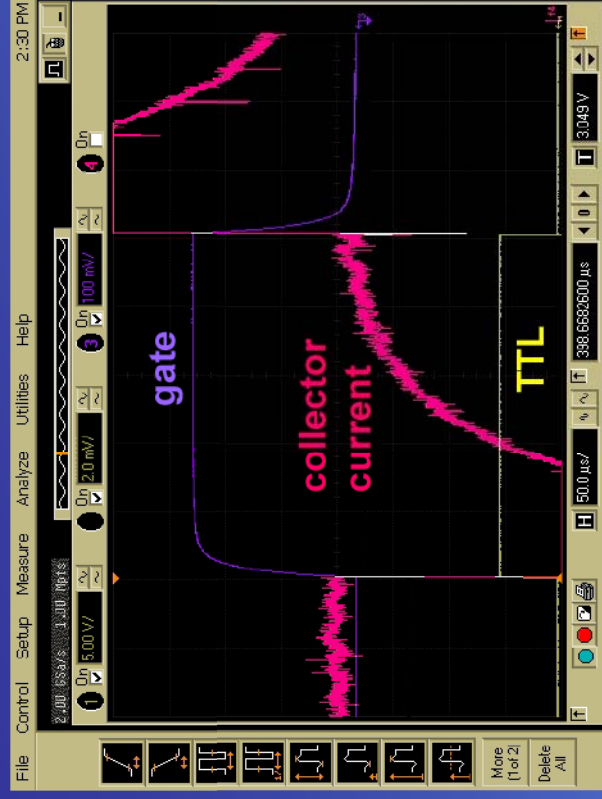
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Low Turn-on Voltage

$$V_{\text{gate}} = 21 \text{ V}$$

$$V_{\text{gate}} = 23 \text{ V}$$



FIRST MEASURED

FEA TWT CURRENT AT 23 V

$\updownarrow = 1 \text{ nA}$

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The oscilloscope displays five waveforms: collector (red), gate (purple), gate-base (yellow), base (green), and TTL (blue). The collector current is annotated as 121 mA. The gate-base voltage is annotated as 79 V. The time scale is set to 5.00 μs/div, and the total time shown is 20.0711000 μs. The voltage scale is 50.0 V/div. The gate signal is a square wave, while the collector, gate-base, and base signals show transient behavior during switching.

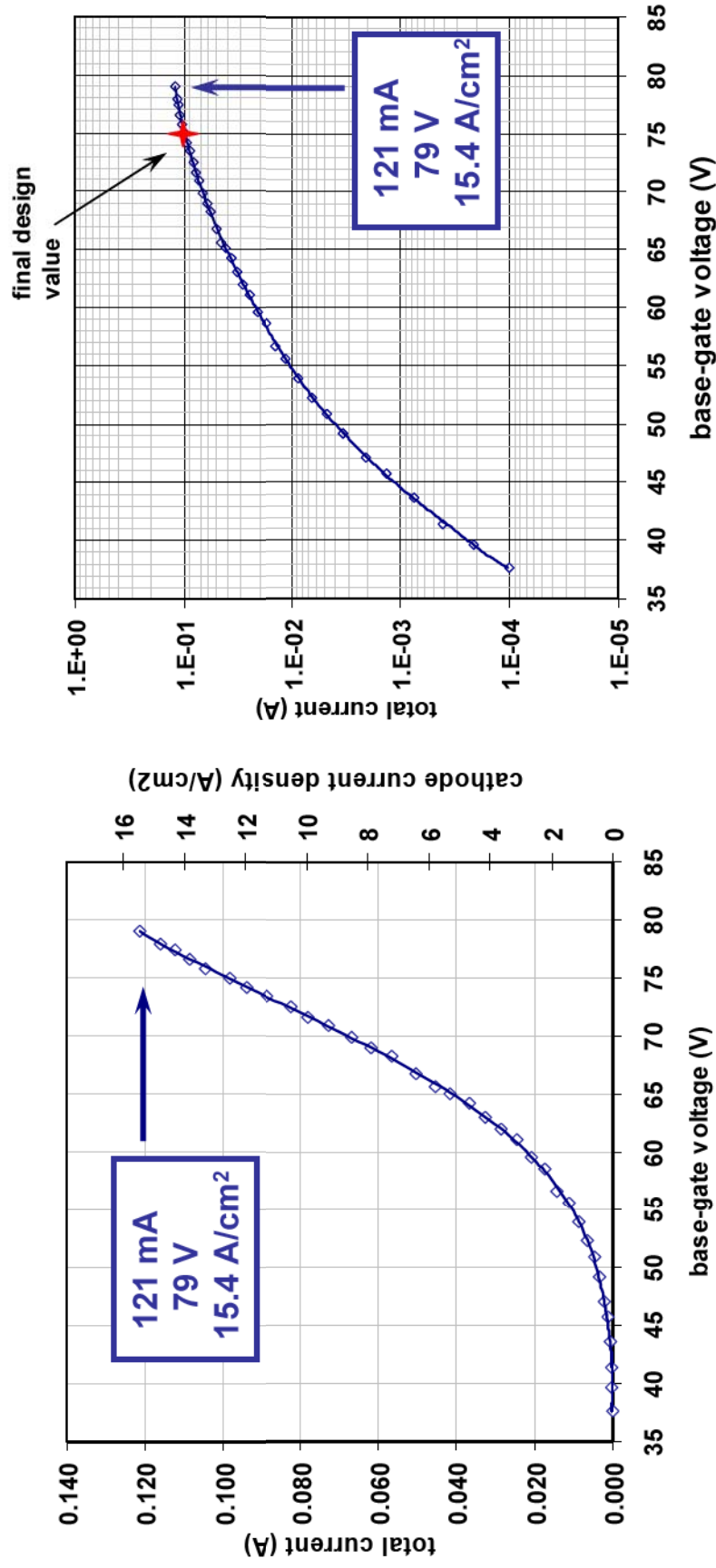
Experimental Results



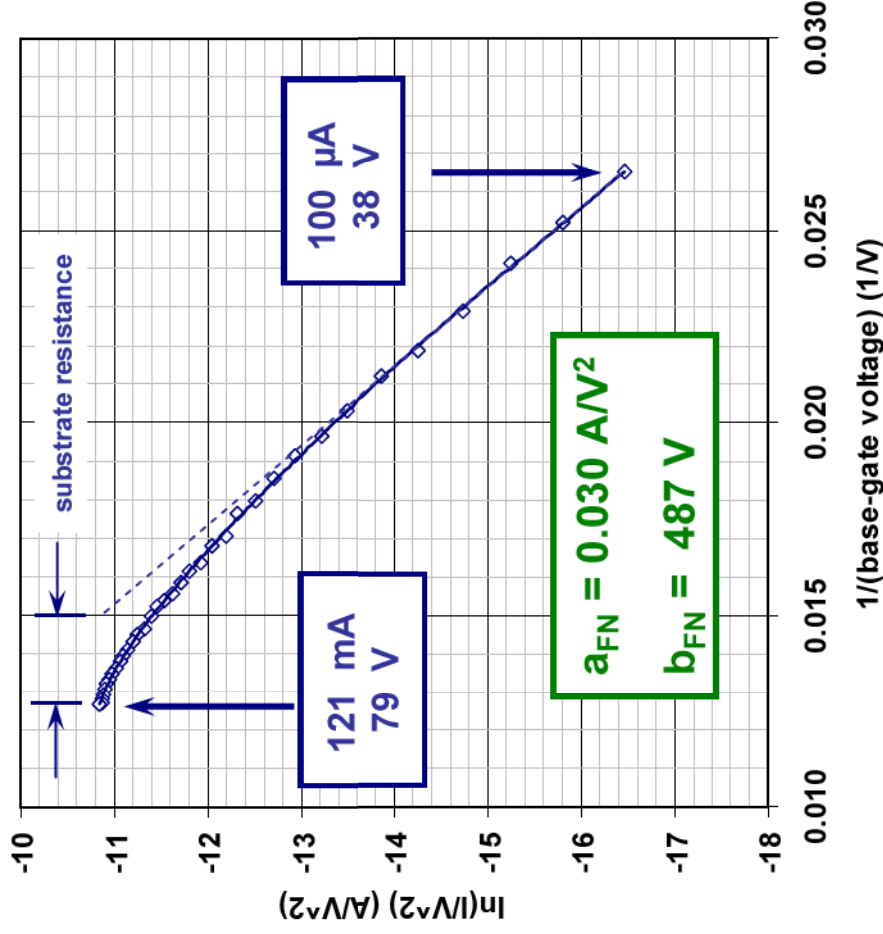
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Measured FEA Emission vs. Base-Gate Voltage



Experimental Results



Fowler Nordheim Emission

$$I = a_{FN} V_{BG}^2 \exp \left(-\frac{b_{FN}}{V_{BG}} \right)$$

$$\ln(I / V_{BG}^2) = \ln(a_{FN}) - \frac{b_{FN}}{V_{BG}}$$

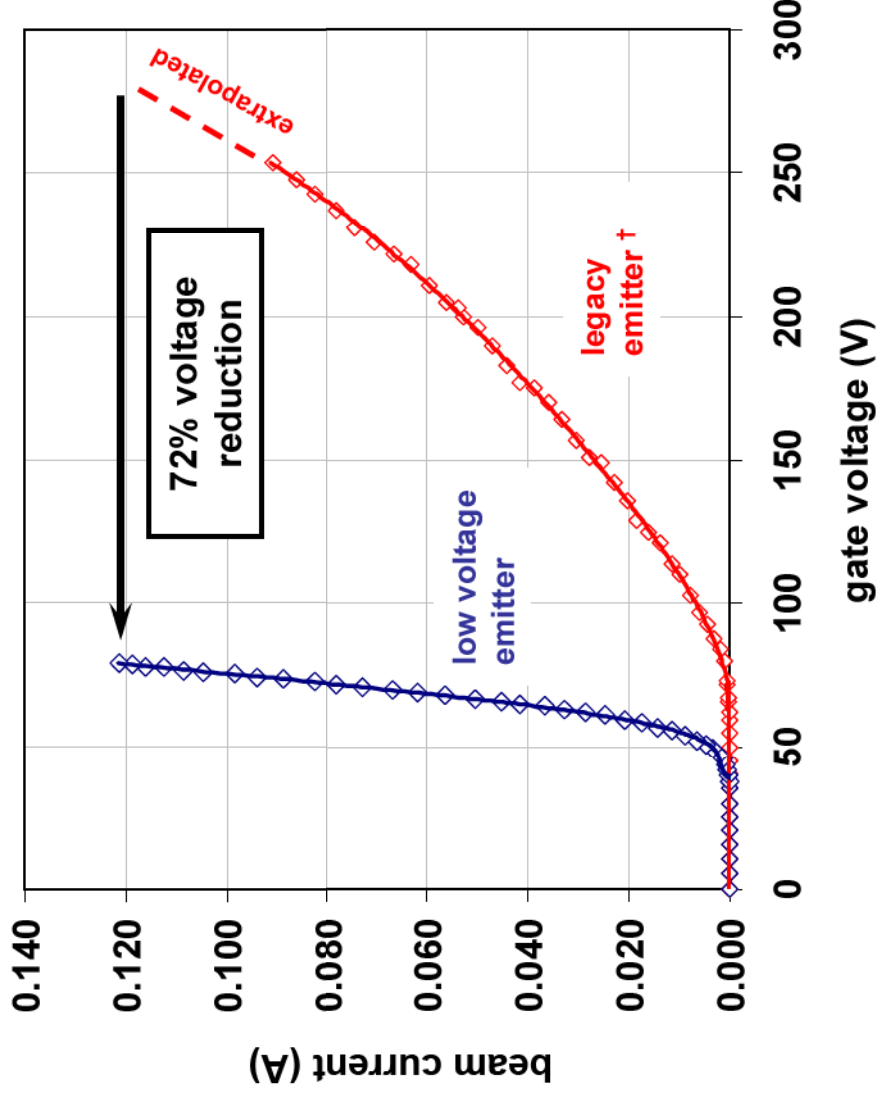
Experimental Results



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Operating-Voltage Reduction with New Low-Voltage Emitters



At maximum current

$$V_{\text{low voltage}} = \underline{79 \text{ V}}$$

$$V_{\text{legacy}} = \underline{280 \text{ V}}$$

$$\frac{V_{\text{low voltage}}}{V_{\text{legacy}}} = 0.28$$

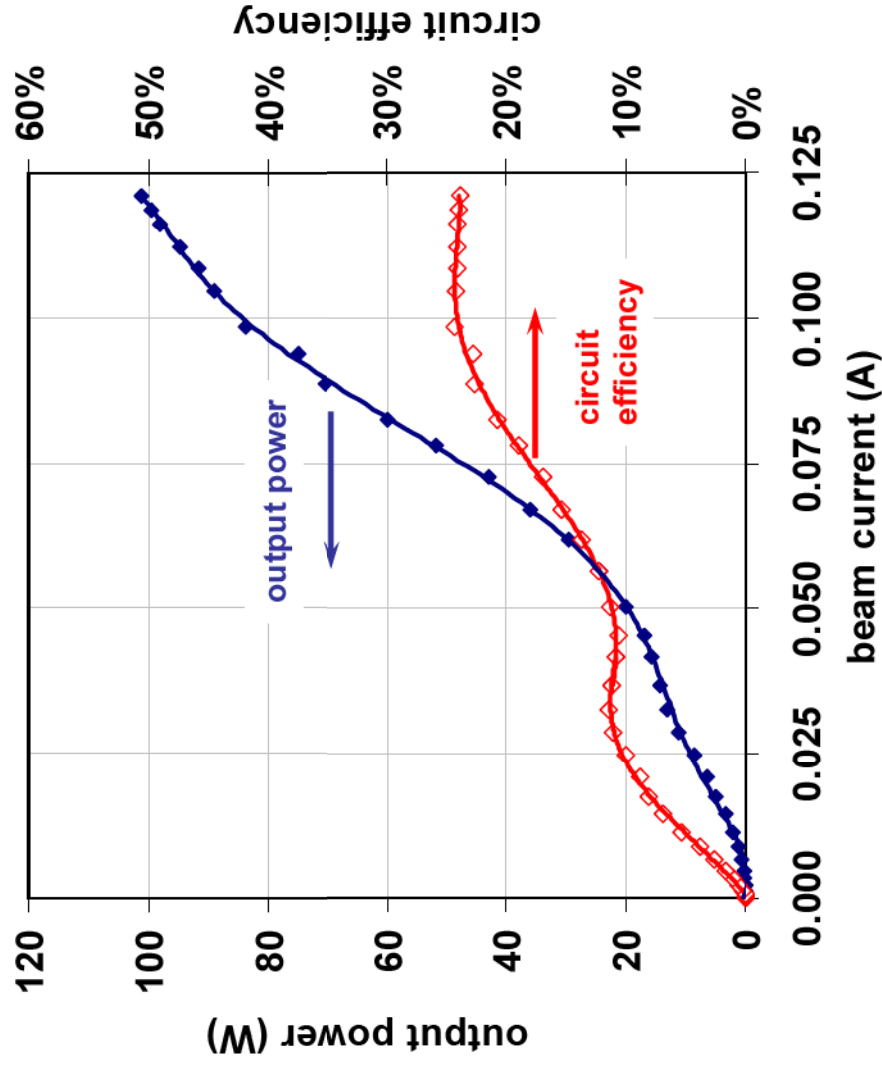
† D. R. Whaley, et al., *IEEE Trans. on Plasma Science*, Vol. 28, No. 3, p. 727-747 (2000).

Experimental Results



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Output Power and Efficiency



At maximum current

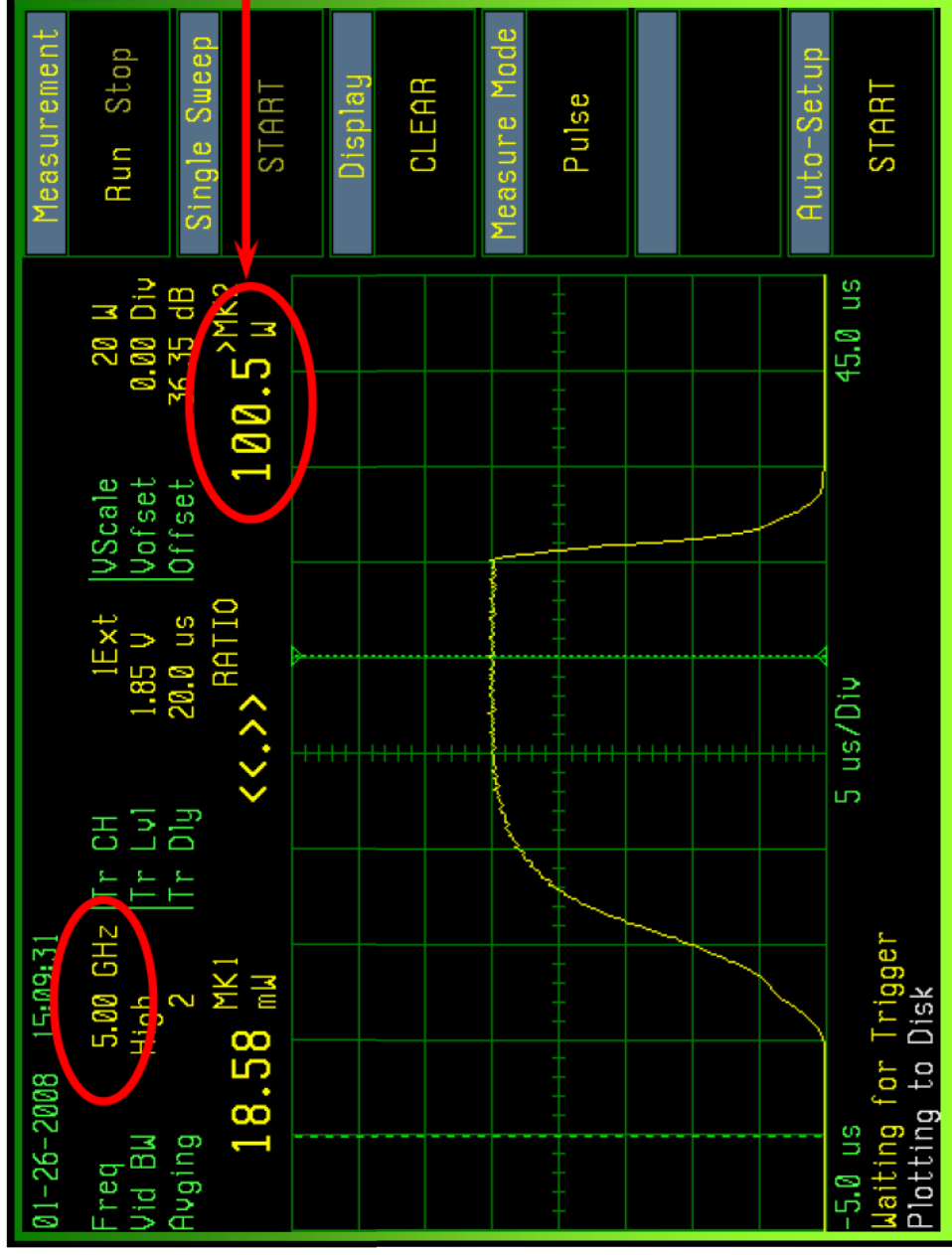
V_{beam}	3500 V
I_{beam}	120 mA
Frequency	5.0 GHz
Small Signal Gain	32.7 dB
Sat Power	100 W
Sat Gain	22.1 dB
Circuit Efficiency	24 %

Experimental Results



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Peak Power Analyzer – 120 mA



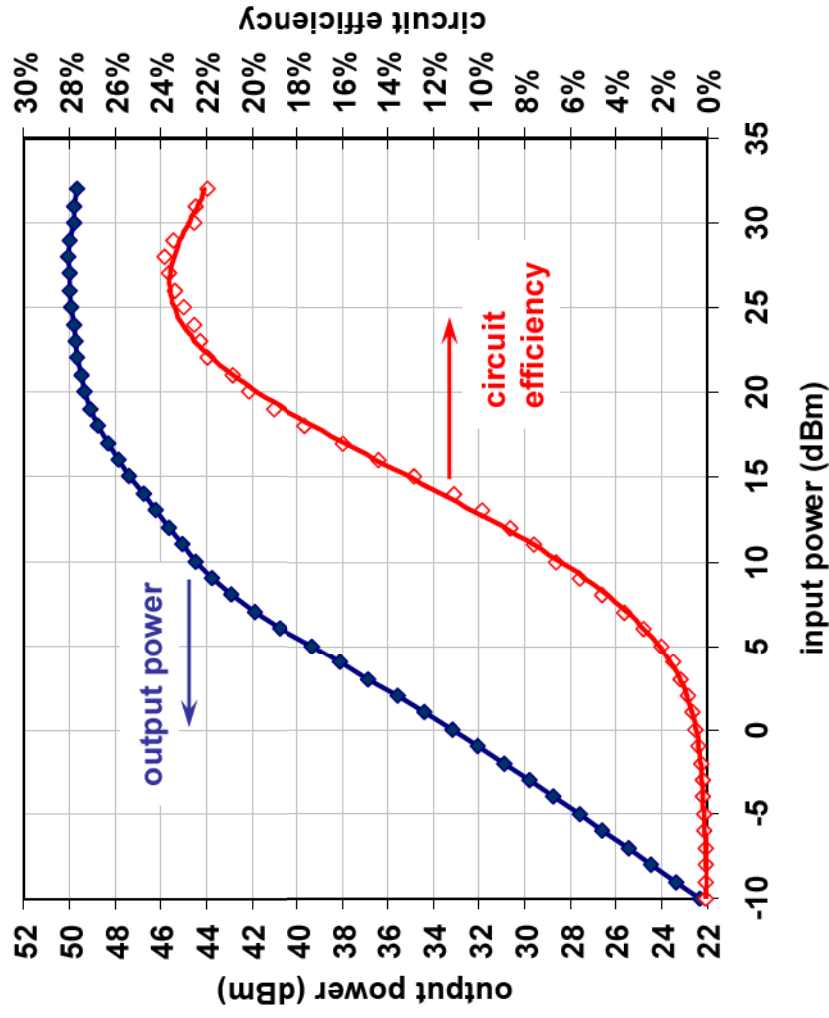
100.5 W
50.0 dBm
5.0 GHz

Experimental Results



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Drive Curve – 120 mA, 5GHz



V_{beam}	3500 V
I_{beam}	120 mA
Frequency	5.0 GHz
Small Signal Gain	32.7 dB
Sat Power	100 W
Sat Gain	22.1 dB
Max Circuit Efficiency	24 %

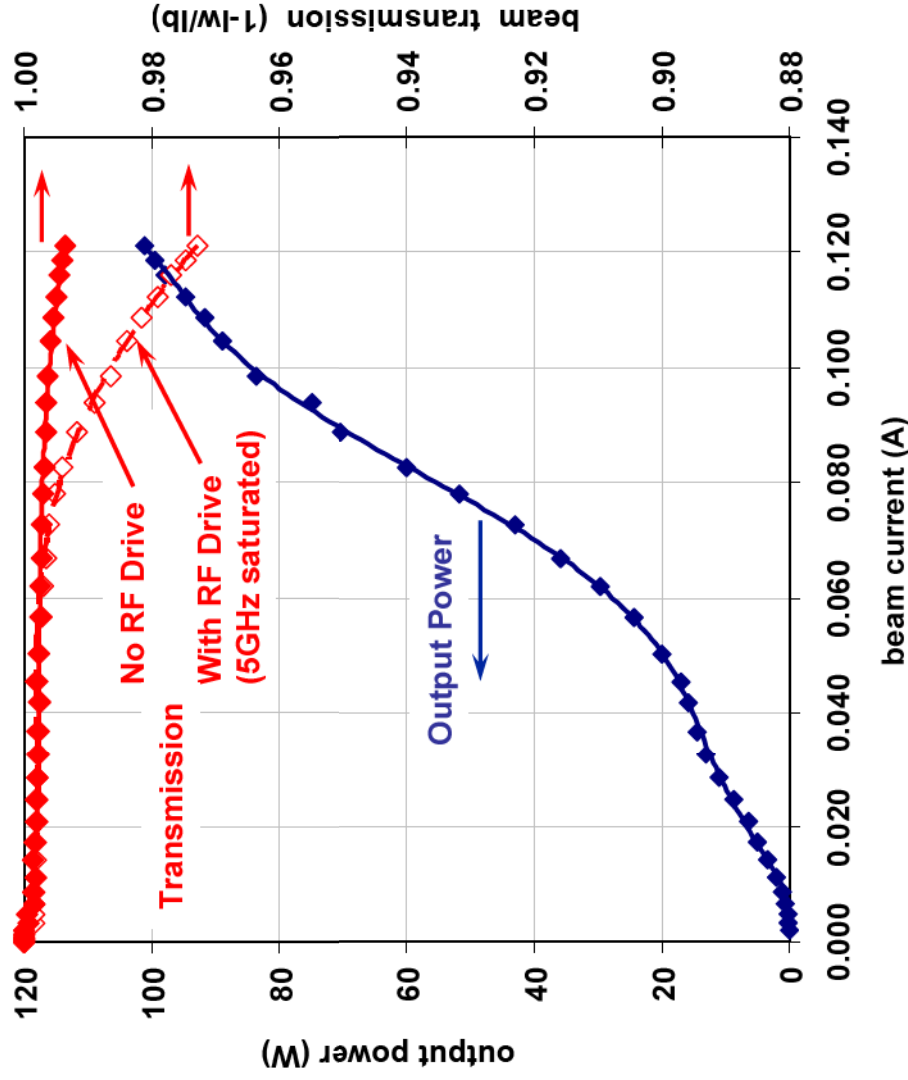
Experimental Results



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FEA Beam Control



Beam
Transmission
No RF Drive – 99.4%
Sat RF Drive – 97.3%

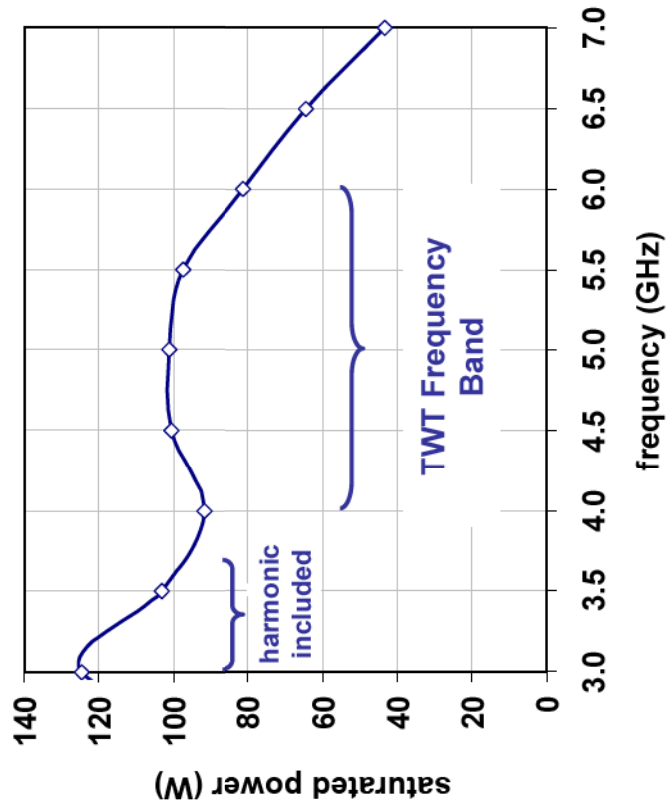
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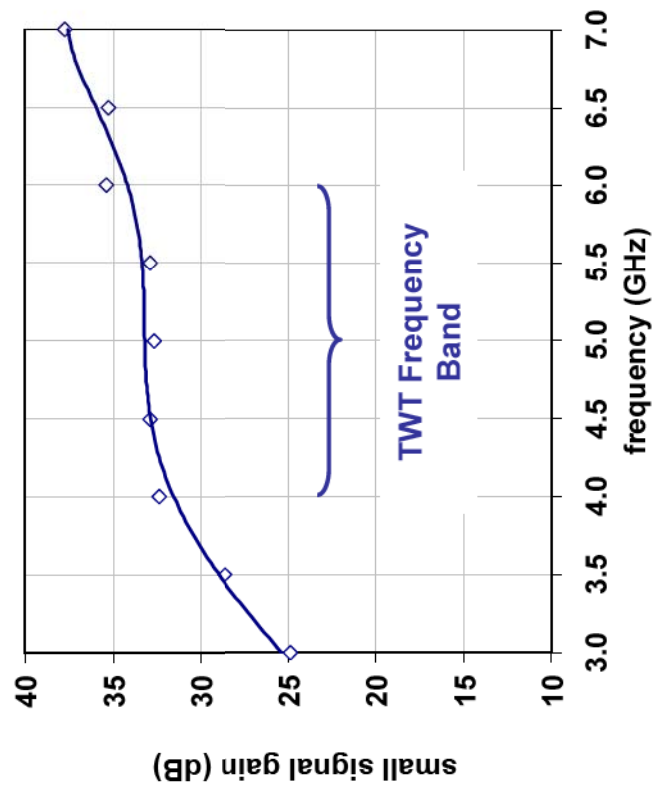
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Saturated Power

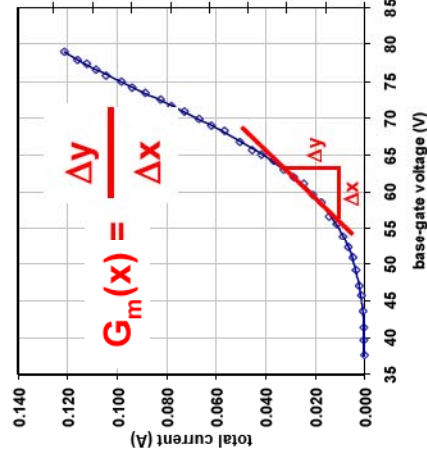


Small Signal Gain



Transconductance

- $G_m = dI/dV_{b-g}$
- Local slope of I/V curve
- Measure of current emission sensitivity to applied voltage
- Changes with applied voltage and emission current
- Measured in Siemens or A/V



High Transconductance Cathodes

Advantages

- Generally means low turnon voltage and low operating voltage
- Low cathode electrical stress
- Low gate surge currents and gate heating during high PRF pulsed operation
- RF-modulated operation possible
- Offsets low capacitance requirement for RF modulated operation

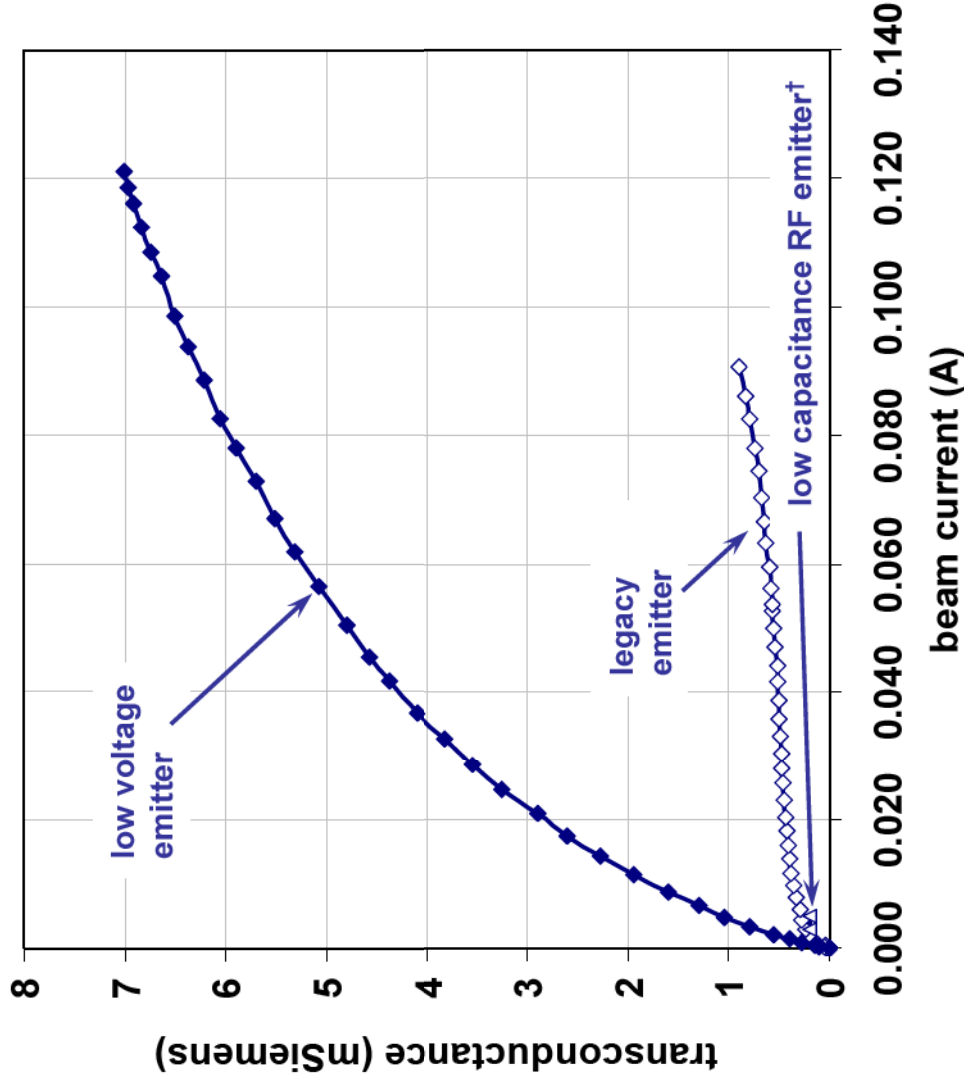
Disadvantages

- Current emission sensitive to power supply drift
- Power supply ripple can generate carrier sidebands due to unintended baseband current modulation

Experimental Results



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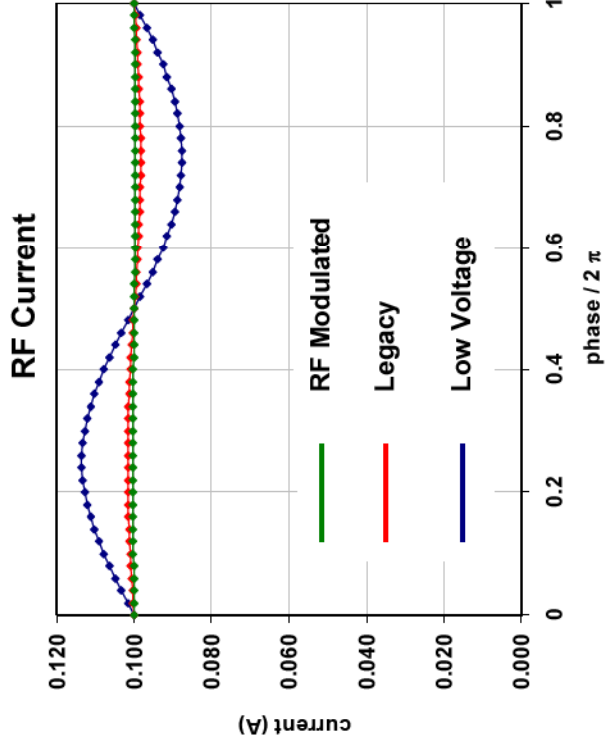
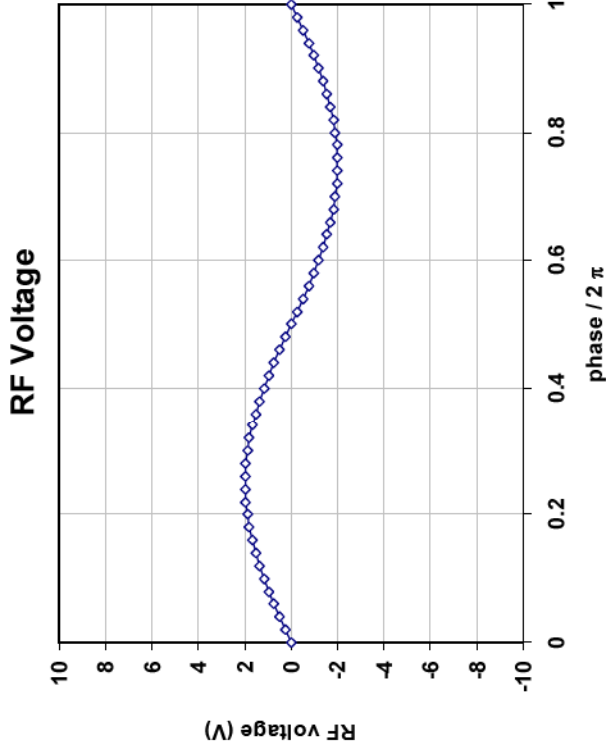
Emitter Type	max G_m
RF Modulated	0.20 mA/V
Legacy	0.89 mA/V
Low Voltage	7.01 mA/V

[†] D. R. Whaley, et al., *IEEE Trans. on Plasma Science*, Vol. 30, No. 3, p. 998-1008 (2002).

Experimental Results

- High Transconductance Can Offset Need for Low Capacitance in RF Modulated Cathodes

$$Modulation\ Efficiency = \frac{\Delta I_{RF}}{I} \propto \underbrace{\frac{\partial I}{\partial V}}_{\text{transconductance}} \times \underbrace{\Delta V_{RF}}_{\text{inversely with capacitance}}$$

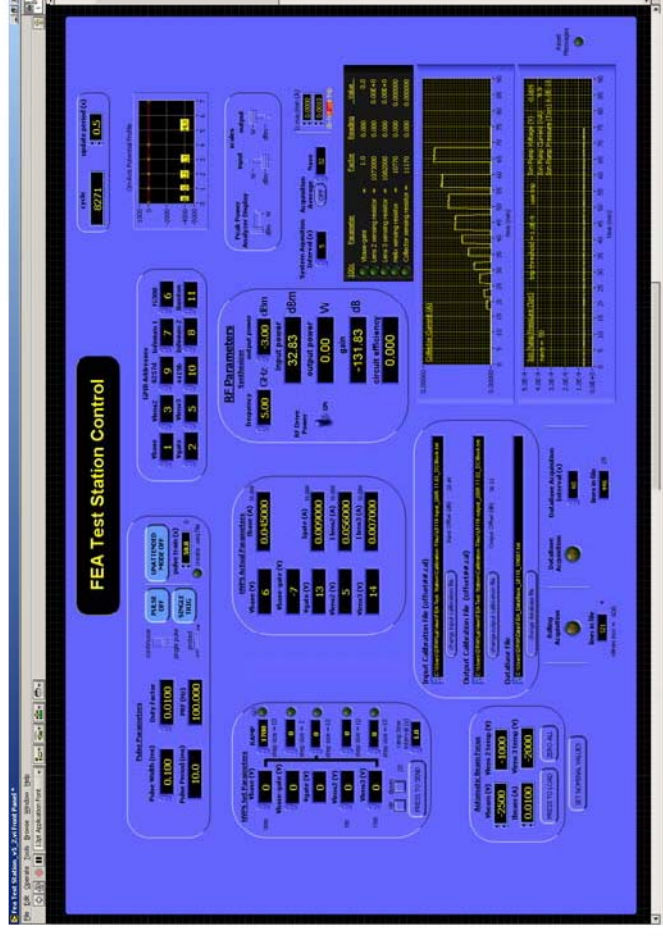


Experimental Results

Life Tests

- LabView data control and acquisition system records all TWT operating parameters vs. time

- time stamp
- pulse parameters (pulse width, duty factor)
- base voltage
- gate voltage
- gun lens voltages
- gun lens currents
- helix current
- collector current
- RF input power
- RF output power
- vacuum pressure



Experimental Results

Life Test Summary

- 10% Duty Operation at 10mA, 20mA, 40mA, 60mA, and 80mA
- 1% Duty Operation at 100mA (85W)
- Single pulsing up to 120mA (100W)
- Total 1% Duty Pulse Time – 58 hours
- Total 10% Duty Pulse Time – 80 hours
- Total Pulse Time – 153 hours
- Total Number of Database Points – 56 k
- Total FEA Pulses – 826 M

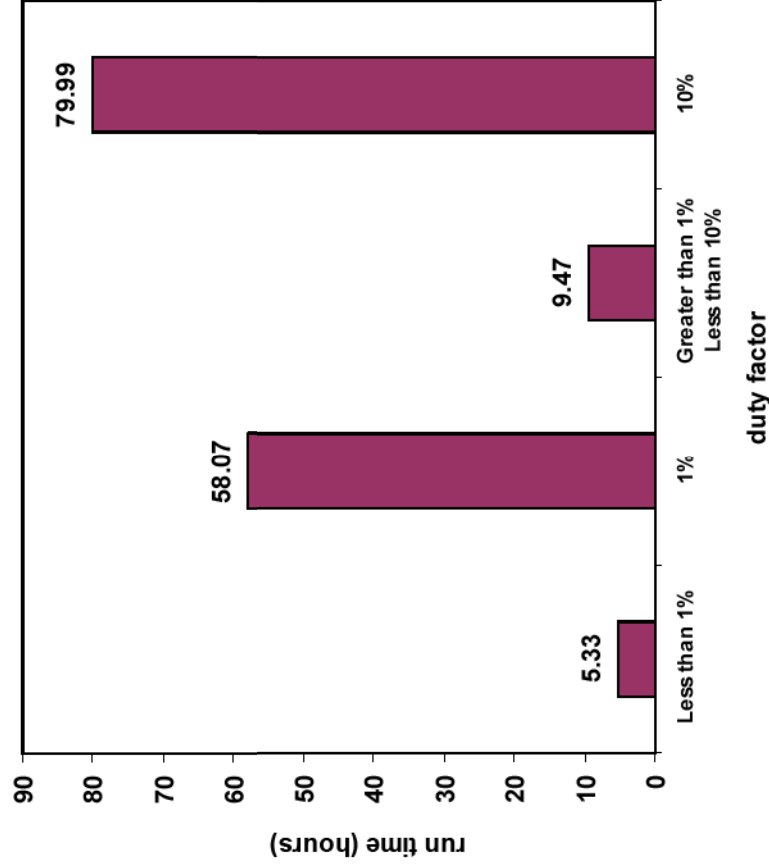
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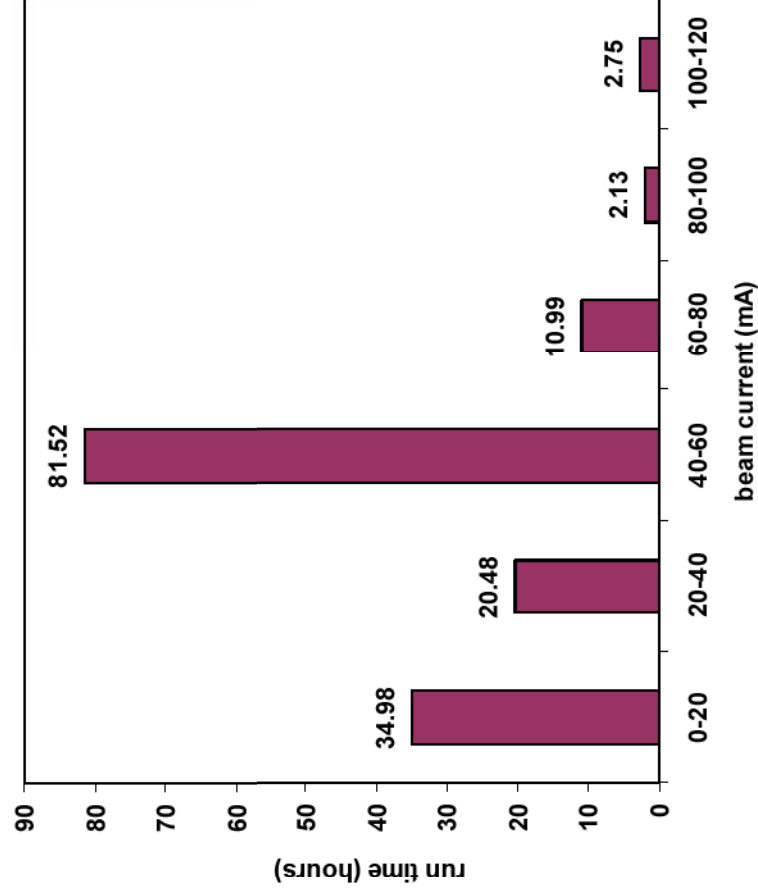
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Duty Factor

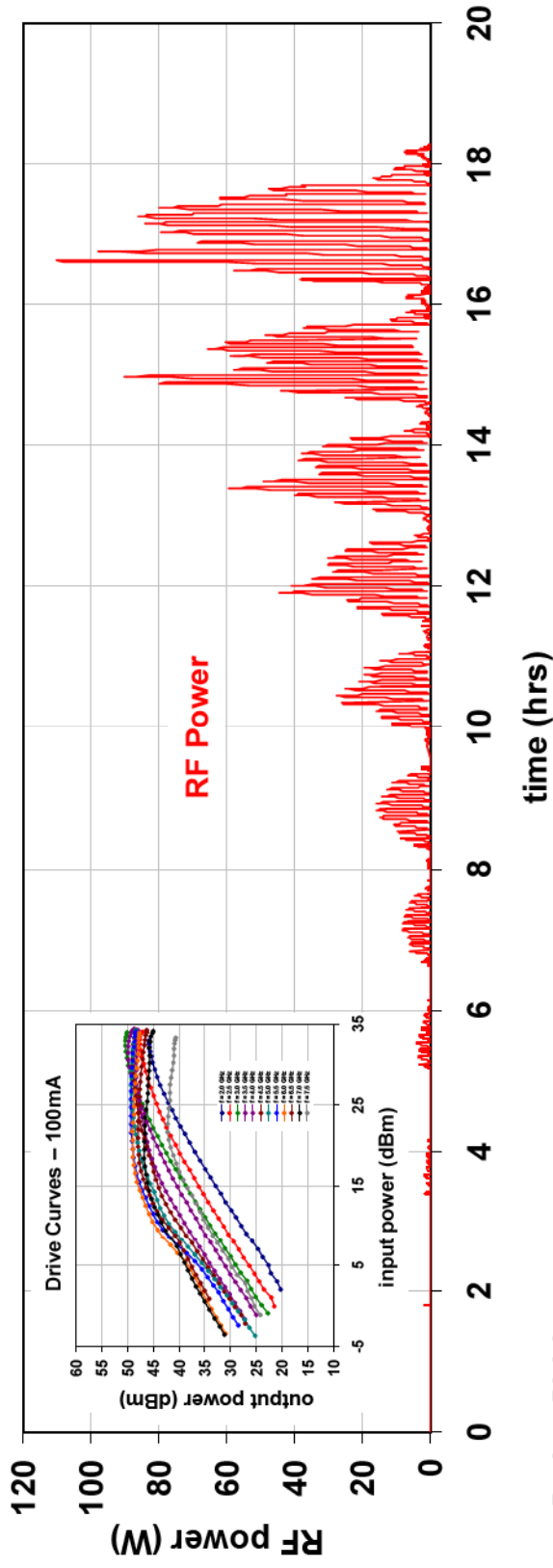
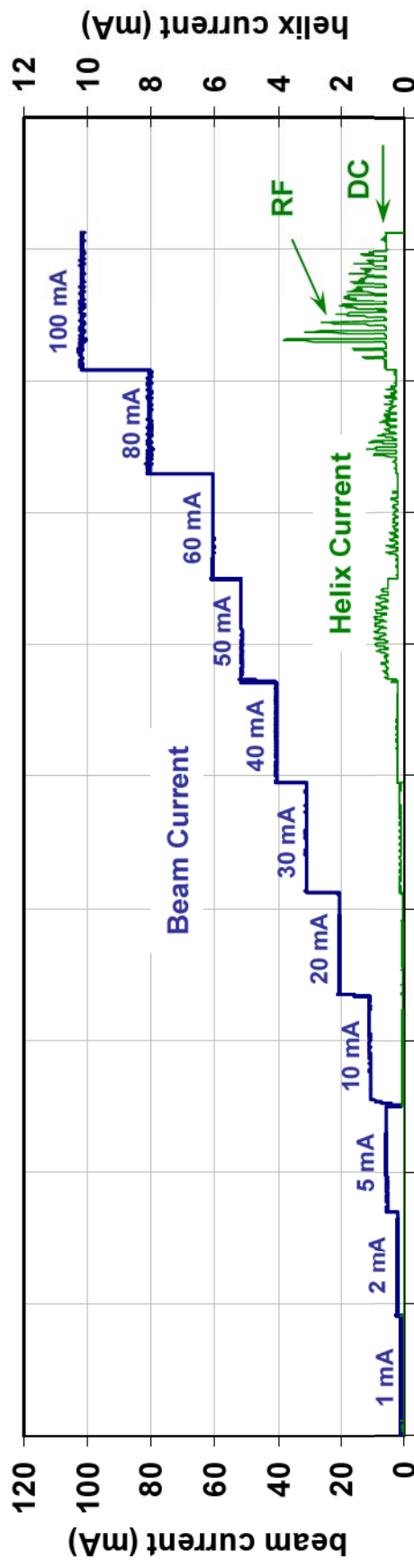


Beam Current (Peak)



Experimental Results

Device Characterization

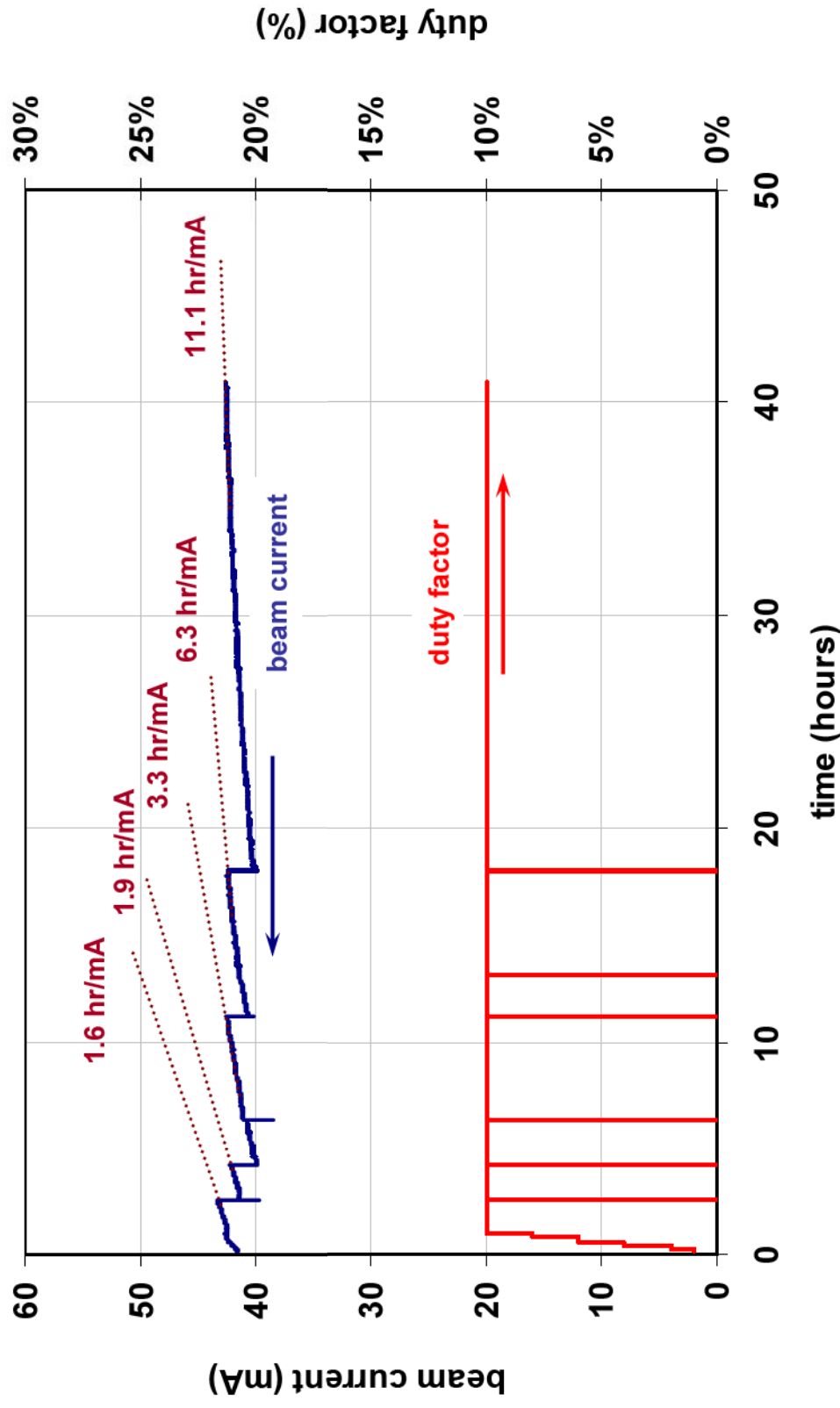


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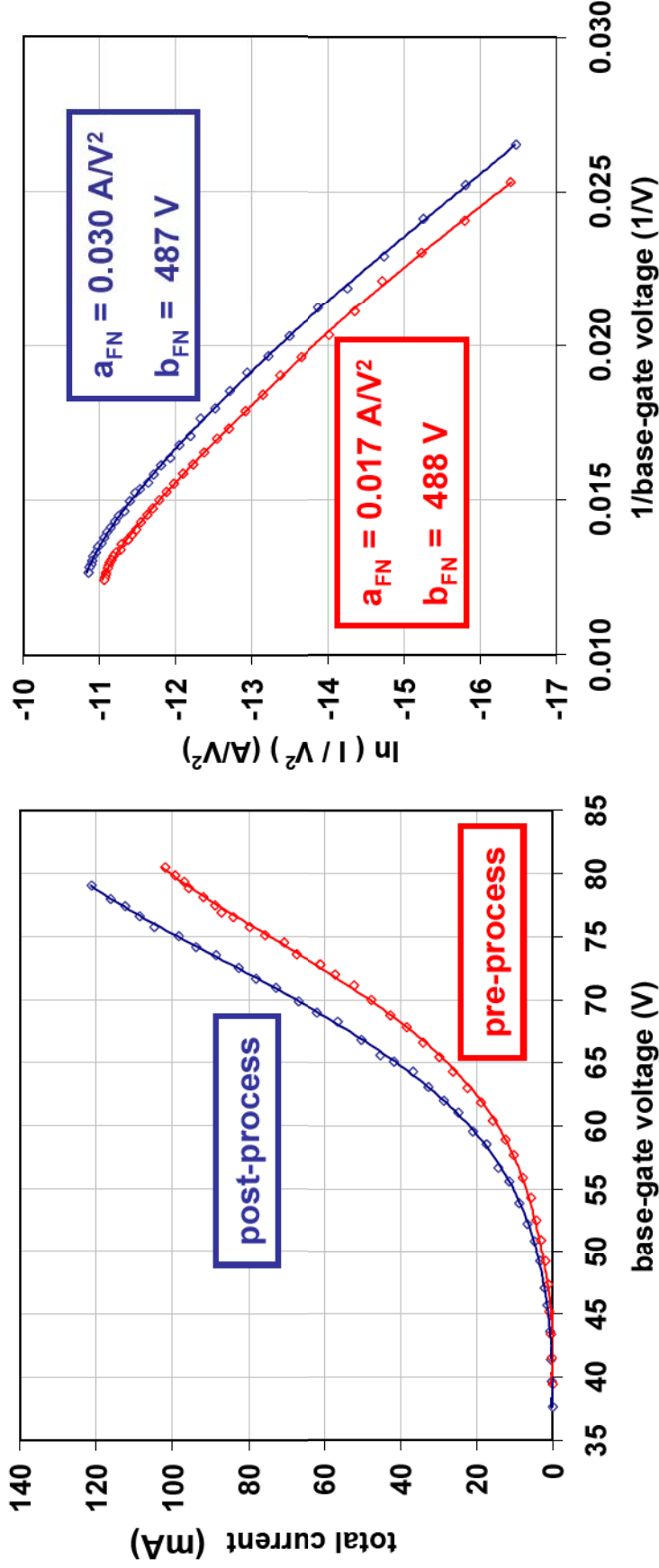
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High Duty Processing



Experimental Results

High Duty Processing

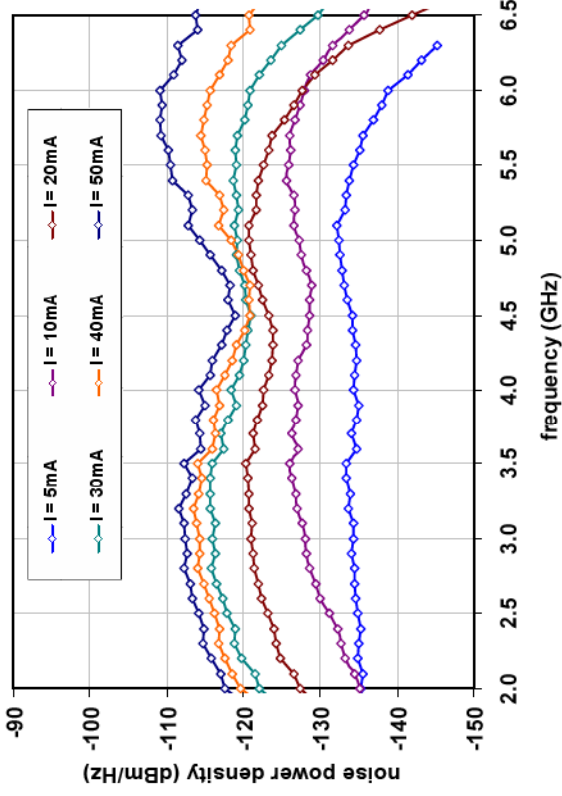
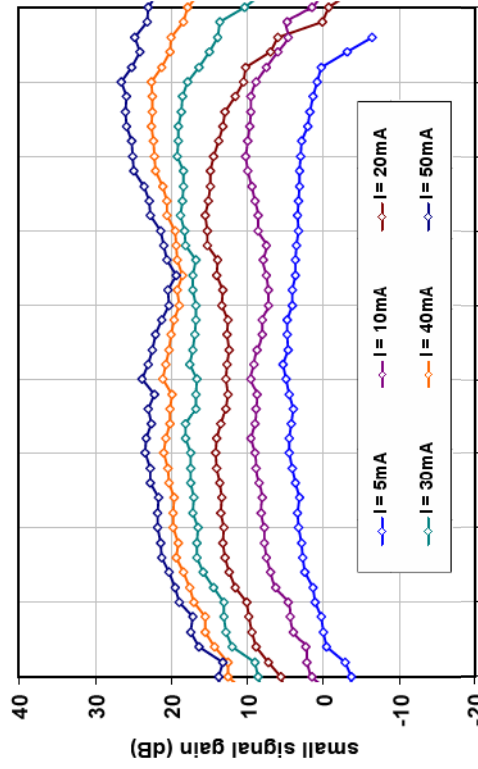


- High duty processing results in significant increase in a_{FN} , b_{FN} remains constant
- Implies that the active area of the cathode is increasing, work function unchanged
- Change appears to be permanent (time scale of weeks or longer)

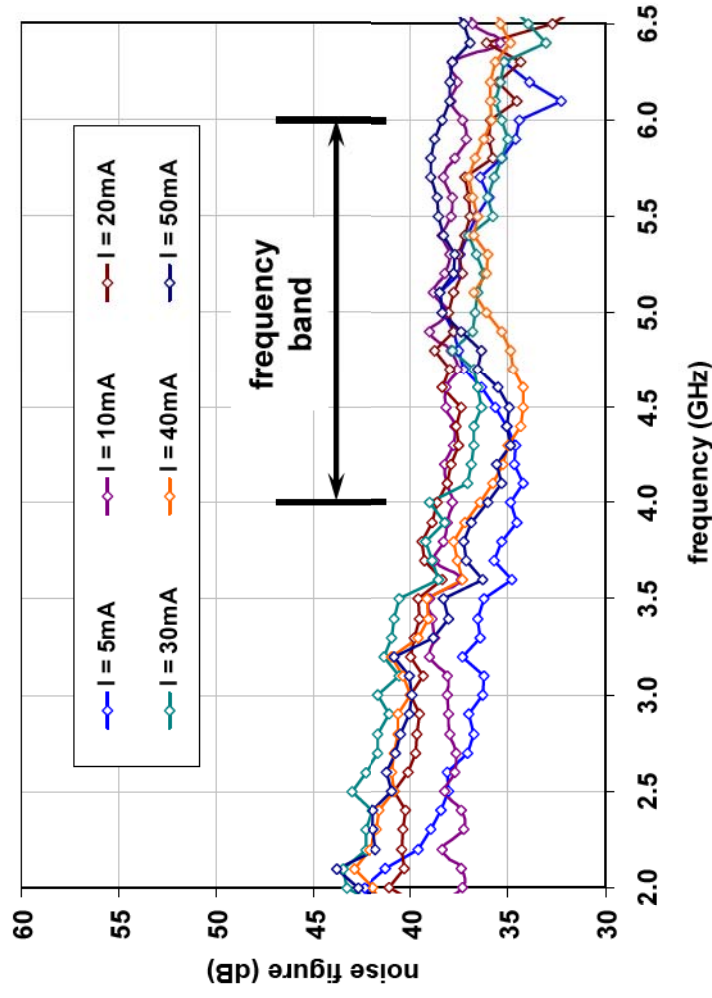
Experimental Results



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Noise Figure vs. Freq + Current



$$\text{NPD} = -174 \text{ dBm/Hz} + G \text{ (dB)} + \text{NF (dB)}$$

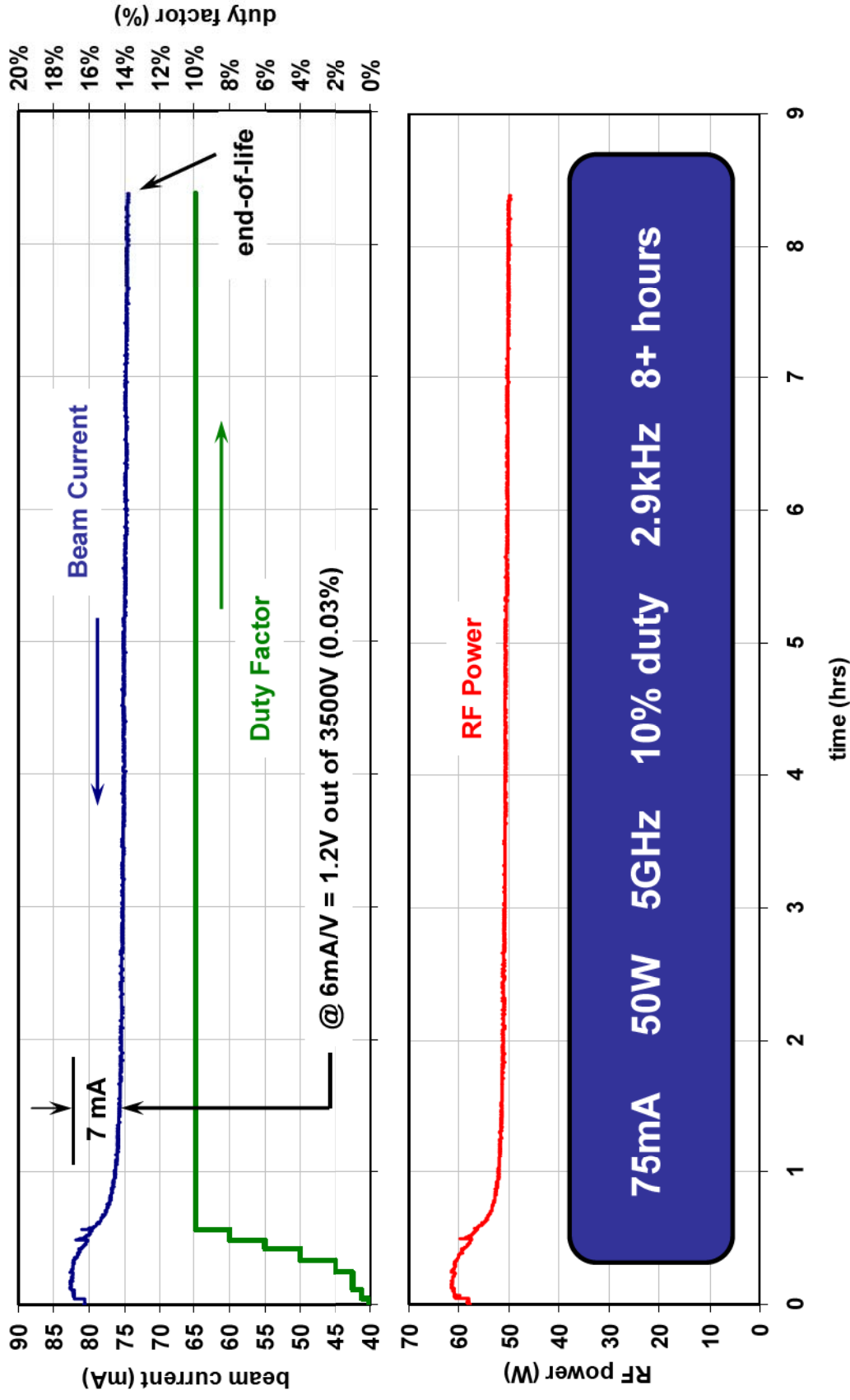
- In-band noise figure = 35-39 dB up to 50mA
- Improved method will replace thermal noise with calibrated noise source

Experimental Results



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Operation at Max Average Current





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Conclusions

- Developed C-Band TWT specific for high current density field emitter array operation
- Demonstrated 72% cathode voltage reduction for full current operation
- Demonstrated TWT operation up to 120 mA, 15.4 A/cm², 100 W at 5GHz, 33dB ssg, 22dB sat gain, 24% circuit efficiency, 99% (97%) DC (RF) transmission
- Transconductance demonstrated at 8x that of legacy SRI FEAs
- Life tests conducted up to 100 mA (12.7A/cm²) – 153 hrs total – 80mA at 10% duty highest average current
- Noise figure measured vs. current and frequency up to 50mA
- Time dependent changes in emission appear to be due to both cathode effective area increase and power supply variation with time
- Second cold cathode TWT built with modified operating characteristics for improved reliability

Acknowledgement



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