NASA/CR—2018-219907

Space Qualified 200-Watt Q-band Linearized Traveling-Wave Tube Amplifier

Neal Robbins, David Eze, Helen Cohen, Xiaoling Zhai, William McGeary, and William Menninger
L3 Technologies, Inc., Electron Devices Division, Torrance, California

Morgan Chen and Eddie Rodgers
L3 Technologies, Inc., Narda Microwave West, Folsom, California

June 2018

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/CR—2018-219907

Space Qualified 200-Watt Q-band Linearized Traveling-Wave Tube Amplifier

Neal Robbins, David Eze, Helen Cohen, Xiaoling Zhai, William McGeary, and William Menninger
L3 Technologies, Inc., Electron Devices Division, Torrance, California

Morgan Chen and Eddie Rodgers
L3 Technologies, Inc., Narda Microwave West, Folsom, California

Prepared under Contract NNC12CA45C

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

June 2018

Acknowledgments

Initial funding for the 9922H Q-band TWT design was provided under NASA Glenn Research Center contract no. NNC12CA45C. Dr. Rainee N. Simons served as the contracting officer technical representative (COTR).

This report contains preliminary findings, subject to revision as analysis proceeds.

Level of Review: This material has been technically reviewed by NASA expert reviewer(s).

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

Space Qualified 200-Watt Q-band Linearized Traveling-Wave Tube Amplifier

Neal Robbins, David Eze, Helen Cohen, Xiaoling Zhai, William McGeary, and William Menninger
L3 Technologies, Inc.
Electron Devices Division
Torrance, California 90505

Morgan Chen and Eddie Rodgers
L3 Technologies, Inc.
Narda Microwave West
Folsom, California 95630

Abstract

L3 Technologies Electron Devices Division, (L3 EDD) and L3 Technologies Narda Microwave West (L3 NMW), are completing space-flight qualification for a 200-watt Q-band linearized channelized traveling-wave tube amplifier (LCTWTA) capable of over 5 GHz instantaneous bandwidth in a conduction-cooled package. This report will discuss the LCTWTA performance, manufacturing and flight qualification test results.

Introduction

The model 2600H linearized, channel-amplifier traveling-wave tube amplifier (LCTWTA), designed and fabricated by L3 Technologies Electron Devices Division (L3 EDD) and Narda Microwave West (L3 NMW), consists of a linearized channel amplifier (LCAMP), traveling-wave tube (TWT), and electronic power conditioner (EPC), which have all completed or nearly completed flight qualification testing. Producing up to 200 W of CW saturated RF power over bandwidths over up to 5.0 GHz in the 37.5-to-42.5 GHz Q frequency band; this LCTWTA represents the highest CW power helix TWT qualified for space applications at Q-band. It maintains typical efficiency, linearity and noise performance. In addition, a linearized, channel amplifier for the same band is completing qualification at L3 Technologies Narda Microwave West (L3 NMW). Together, the 9922H TWT and the linearized channel amplifier, combined with an L3 EDD electronic power conditioner such as the 2600H, will provide unprecedented amplifier performance for commercial space downlink applications.

Background

This report discusses the L3 EDD Q-band LCTWTA. It produces up to 200 W of CW, linearized saturated RF power over up to 5 GHz in the Q frequency band. Figure 1 shows the model 2600H EPC with the model 9922H conduction-cooled TWT next to the L3 NMW linearizer and channel amplifier (LCAMP).

Traveling-Wave Tube (TWT)

The TWT model 9922H employs a helical RF circuit with periodic, permanent magnet (PPM) focusing packaged for conduction cooling. The electron gun is a dual-anode, isolated-focus-electrode design, and is designed for greater than 15 years of mission life. The helix circuit is designed to provide CW saturated RF output power up to 200 W RF over the 37.5 to 42.5 GHz Q-band frequency range. The 9922H was designed primarily using the Naval Research Laboratory codes CHRISTINE 3D (Ref. 1) and MICHELLE (Ref. 2).

TWT Qualification

The model 9922H TWT is completing flight qualification. Measured RF performance at ambient temperature is shown in Table I.

The TWT body current at saturated drive level is below 0.6 mA while the output power exceeds 200 W across 37.5 to 42.5 GHz with an average efficiency of 60 percent. The following additional test results are presented in the Appendix:

- RF output Power vs. time at a fixed frequency of 40 GHz
- Input and output return loss vs. frequency
- Single tone RF output power vs. input drive from saturation at several frequencies
- Saturated output power vs. frequency
- Small signal gain and phase vs. frequency
- Collector currents and body current vs. input power relative to saturation
- Total DC power, RF output power, and thermal dissipation vs. input power relative to saturation

The overall space-flight qualification effort includes a range of operating and nonoperating environmental tests. TWT qualification testing began after exhaustive acceptance test processing and performance quantification. Qualification testing includes random vibration testing, pyrotechnic shock testing, and thermal-vacuum cycling. The random vibration is at levels of up to 18.9 Grms for a minimum of 3 min per axis. For shock testing a high-performance vibration table was used to simulate a shock

Figure 1.—2600H EPC (upper left) with 9922H TWT (middle) and L3 NMW LCAMP (lower right).

TABLE I.—9922H TWT PERFORMANCE

Frequency, GHz	37.5	40.0	42.5	(No drive)
Drive level	Saturated			
Iw, mA	0.42	0.44	0.55	0.13
Pin, dBm	0.3	–1.2	–0.3	-----
Saturated Pout, W	204	208	201	-----
Saturated Gain, dB	52.8	54.4	53.4	-----
Total DC, W	335	347	346	112
Thermal Dissipation, W	131	139	145	112
Overall Efficency, %	61.0	59.9	58.2	-----

pulse over the frequency range from 100 Hz to 10 KHz. Each test was performed three times per axis for a total of 9 pyrotechnic shock qualification pulses at levels of up to 2590 g's. Thermal vacuum testing is now being performed over all operating conditions from nonoperating to full RF power. Sixteen (16) thermal vacuum cycles will be performed over the temperature range of –20 to 86 °C. Four "cold starts" will soak the nonoperating TWT to thermal stability at –35 °C and then initiating a full RF power start and CW operation. The unit will also demonstrate nonoperating survival from –35 to 95 °C. Additional details on the sinusoidal vibration, random vibration, shock, thermal vacuum cycles, environmental qualification performance, and life test experience are presented in the Appendix.

At each intermediate step and again once all environmental testing completed, the TWT will be exercised through a full functional and operational test regime.

Electronic Power Conditioner (EPC)

The electronic power conditioner (EPC) shown in Figure 1 is model 2600H, qualified in 2016 (Ref. 3). This EPC is capable of processing up to 600 W of DC power at voltages of up to 12 kV. The EPC can be configured to accept either regulated or unregulated spacecraft bus voltages of up to 100 V. The EPC efficiency ranges between 91 and 95 percent depending on the spacecraft bus voltage interface and environmental extremes requirements. At power levels below approximately 40 W, the Q-band TWT can mate to the lighter L3 EDD model 2000H or 2410H EPCs which provide cathode voltages up to 7 kV.

Linearized Channel Amplifier (LCAMP)

The L3 NMW LCAMP is shown at the lower right in Figure 1. An LCAMP consists of a channel amplifier (CAMP) and linearizer. The CAMP operates in fixed gain mode (FGM) or automatic-level-control (ALC) mode. In ALC mode, a fixed drive level is provided to the linearizer over a wide input dynamic range. In the fixed gain mode (FGM), the CAMP provides a variable gain that may be used for various system purposes such as ground mode testing. The CAMP provides 53 dB linear gain across the 37.5 to 42.5 GHz band. The linearizer is a unity-gain pre-distorter that follows the CAMP. Its purpose is to compensate TWT nonlinearity and provide reduced back-off levels of operation to enhance system linearity, power, and efficiency. Figure 2 shows typical improvement in noise power ratio (NPR) achieved by the linearizer. The LCAMP thermally compensates for the TWTA performance with thermistor-based control circuitry. Both CAMP and linearizer are mounted to a common baseplate and take an 8 V supply with 7 W power consumption. RF input and output connectors are coaxial 2.4 mm.

The LCTWTA has an input dynamic range from –49 to –13 dBm with 36 gain steps in 1.0±0.3 dB increments in FGM. In ALC mode, this LCTWTA has a minimum control range of +2 to –13 dB relative to saturation with 30 gain steps in 0.5±0.25 dB increments, and typically 18 dB range with 36 control increments. The linearizer provides ~5 dB gain expansion and 40° phase expansion over swept power with 20° intentional phase expansion variation across frequency to match TWTA characteristics.

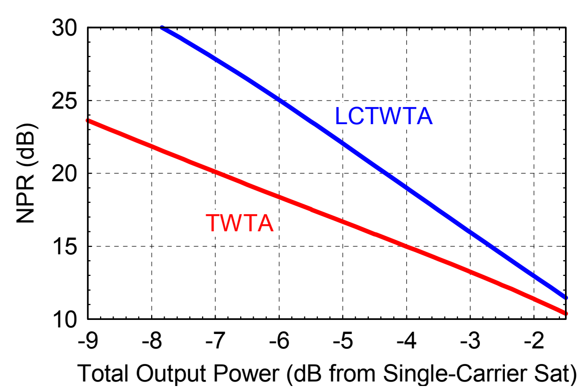


Figure 2.—Simulated LCTWTA NPR performance based on measured EM TWT and LCAMP data.

Conclusion

As a result of the thorough qualification testing, L3 EDD, with support from L3 NMW, is prepared to offer unprecedented Q-band RF amplifier performance from a flight-qualification-tested LCTWTA delivering power levels up to 200 W with LCTWTA efficiencies over 50 percent and NPR approaching 20 dB at 4.5 dB OBO from saturation.

References

1. T.M. Antonsen, D.P. Chernin, S.J. Cooke and B. Levush, “Spurious reflection of space charge fields in TWTAs,” in IEEE Transactions on Electron Devices, vol. 52, no. 5, pp. 755–763, May 2005.
2. J.J. Petillo, E.M. Nelson, J.F. DeFord, N.J. Dionne and B. Levush, “Recent developments to the MICHELLE 2-D/3-D electron gun and collector modeling code,” in IEEE Transactions on Electron Devices, vol. 52, no. 5, pp. 742–748, May 2005.
3. N.R. Robbins, W.L. Menninger, X. Zhai and D.E. Lewis, “Space qualified, 150–300-watt K-band TWTA,” *2016 IEEE International Vacuum Electronics Conference (IVEC)*, Monterey, CA, 2016, pp. 1–2.

Appendix—Additional RF Test Results and Details on Environmental Qualification

Electron Devices

Space Qualified 200-Watt Q-band Linearized Traveling-Wave Tube Amplifier

Neal Robbins, David Eze, Helen Cohen, Xiaoling Zhai
William McGeary, William Menninger, Morgan Chen*, Eddie Rodgers*

L3 Technologies, Electron Devices Division
Torrance, California, USA 90505

* - L3 Technologies, Narda Microwave West
Folsom, California, USA 95630

2018 International Vacuum Electronics Conference
April 22 – 24, 2018
Monterey, USA

This presentation consists of L3 Technologies, Inc. general capabilities information that does not contain controlled technical data as defined within the International Traffic in Arms (ITAR) Part 120.10 or Export Administration Regulations (EAR) Part 734.7-11.

Outline

Electron Devices

- Introduction
- Heritage
- Qualification
- Performance summary
- Conclusion

Q/V Broadband Solution

Electron Devices

Q/V-band spectrum in the context of satellite telecom spans from 37.5 GHz to 42.5 GHz for downlink as well as 47 to 52 GHz for uplink. This is significant because **Q/V-band offers roughly 5 GHz (5,000 MHz) of continuous spectrum for downlink**

	Downlink Frequencies	Spectrum Available by GEO Orbital Position	Antenna Type and Diameter
Q/V-bands	***~40 GHz***	***5,000 MHz***	**Pointed**
Ka-band	~20 GHz	3,500 MHz	Pointed (0.6-1.2m)
Ku-band	~12 GHz	500 MHz	Pointed (0.9-1.2m)
C-band	~4 GHz	500 MHz	Pointed (1.8)
S-band	~3 GHz	70 MHz	Omnidirectional (0.2-0.6m)
L-band	~1.5 GHz	15 MHz	Omnidirectional (0.2-0.6m)

Higher frequency bands offer more available bandwidth.

Export Compliance Statement on Page 1

Q/V-Band Down/Up-link TWTs

Electron Devices

DOWN LINK

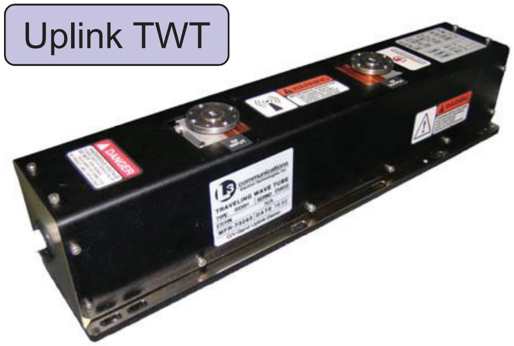
Downlink TWTA

- TWT Model: 9922H
- 200 W, 37.5 – 42.5 GHz
- Initial funding from NASA
- Mates with any EDD EPC
- **Qualification Complete**
- **In production now**

Addresses emerging Q/V band commercial broadband market

- *TWT Model: 8936H
- 200 W, 47.0 – 52.0 GHz
- Uses heritage Q band TWT as a baseline
- Mates to OEM power supply
- **Available 3Q18**

Uplink TWT



UP LINK

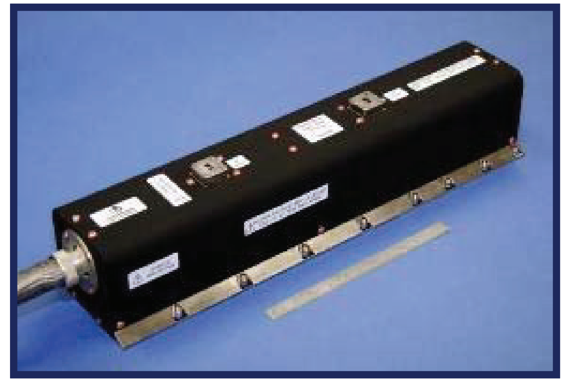
* C. K. Chong "L3 technologies EDD Q/V-band helix TWT 327 for future high-data-rate communications uplink applications," *IEEE 18th Int. Vac. Electron. Conf.*, London, U.K., Apr. 2017

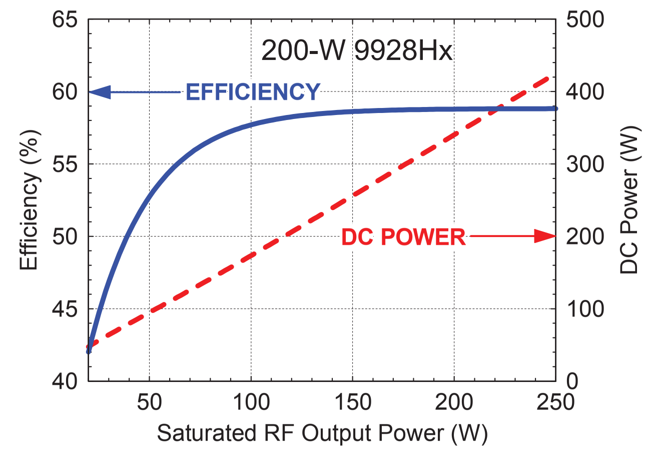
Export Compliance Statement on Page 1

mm-Wave (22-76 GHz) TWT Product Family

Electron Devices

Status	Flight *	Flight *	Production	Production
Parameter	9934Hx	9928Hx	9922Hx	9915Hx
Total Band	22 – 33 GHz	26 – 40 GHz	33 – 50 GHz	50 – 76 GHz
Instantaneous BW	Up to 4 GHz	Up to 5 GHz		Up to 6 GHz
RF Power	20 – 200 W	20 – 200 W	20 – 200 W	10 – 100 W
Saturated Gain	46 – 56 dB	46 – 56 dB	46 – 56 dB	43 – 53 dB
Efficiency**	30 – 60%	30 – 60%	30 – 55%	25 – 45%
Sat Drive	-5 to +1 dBm			-3 to +3 dBm
Phase Shift SS to Sat	45°			
AM/PM Conv. @ Sat	4° /dB			
Gain Ripple	0.5 dB p-p/33 MHz wc			
Gain Slope	0.015 dB/MHz wc			
Input VSWR	2.0:1 max			
Output VSWR	2.0:1 max			
Noise Figure	33 dB max			
C/3IM @ -3 dB	10 dBc			
Dimensions L" x W" x H"	14.1 x 3.5 x 2.7			13.6 x 3.5 x 2.7
Conduction	1500 g (TWT only)			
RF Input Connector	WR 34	WR 28	WR 22	WR 15
RF Output Connector	WR 34	WR 28	WR 22	WR 15
Compatible EPCs	2000Hx, 2300Hx, 2410Hx, 2600Hx, 1693Hx**			2600Hx, 1693Hx**





*- In orbit (Kepler, LRO, SCaN, JPSS, etc.)
** - Depends on RF power level

Acknowledgements
Initial funding for the 9922H Q-band TWT design was provided under NASA Glenn contract no. NNC12CA45C.

Export Compliance Statement on Page 1

mm-Wave Space TWT Production History

Electron Devices

Supporting 8 customers and 13 missions to date

TWTA Model	TWT Model	Frequency (GHz)	Sat Power (Watts)	Ordered Qty	Delivered Qty	Units in orbit	Launch Date
2300HE	9835H	25.5 – 25.8	40	2	2	2	18 Jun 2009
2300HE	9835H	25.5 – 25.8	40	1	1	1	20 July 2012
2302HC	9934HA	26.4 – 27.0	70	2	2	2	18 Nov 2017
2302HC	9934HB	26.4 – 27.0	70	5	0		In production
2000HDA	9934HC	25.3 – 27.5	70	3	0		In production
1641H	955H	31.8 – 32.3	10	2	2	2	15 Oct 1997
2300HD	9935H	31.8 – 32.3	35	2	2	2	6 Mar 2009
2000HBW	9928HA	32.5 – 33.0	70	4	4		(2019)
2302HH	9928HD	33.0 – 36.0	70	4	0		In production
2000HDA	9922HA	40.0 – 42.0	35	30	0		In production
1693HF	9915H	60.5 – 63.5	80	8	8		(2018)
1693HG	9915HA	60.5 – 63.5	35	9	3		In production
1693HK	9915H	60.5 – 63.5	80	2	0		In production
TOTAL				**74**	**22**	**9**	

> 250,000 flight operating hours
No failures or anomalies

Export Compliance Statement on Page 1

Export Compliance Statement on Page 1

Model 9922H – Broadband Performance

Electron Devices

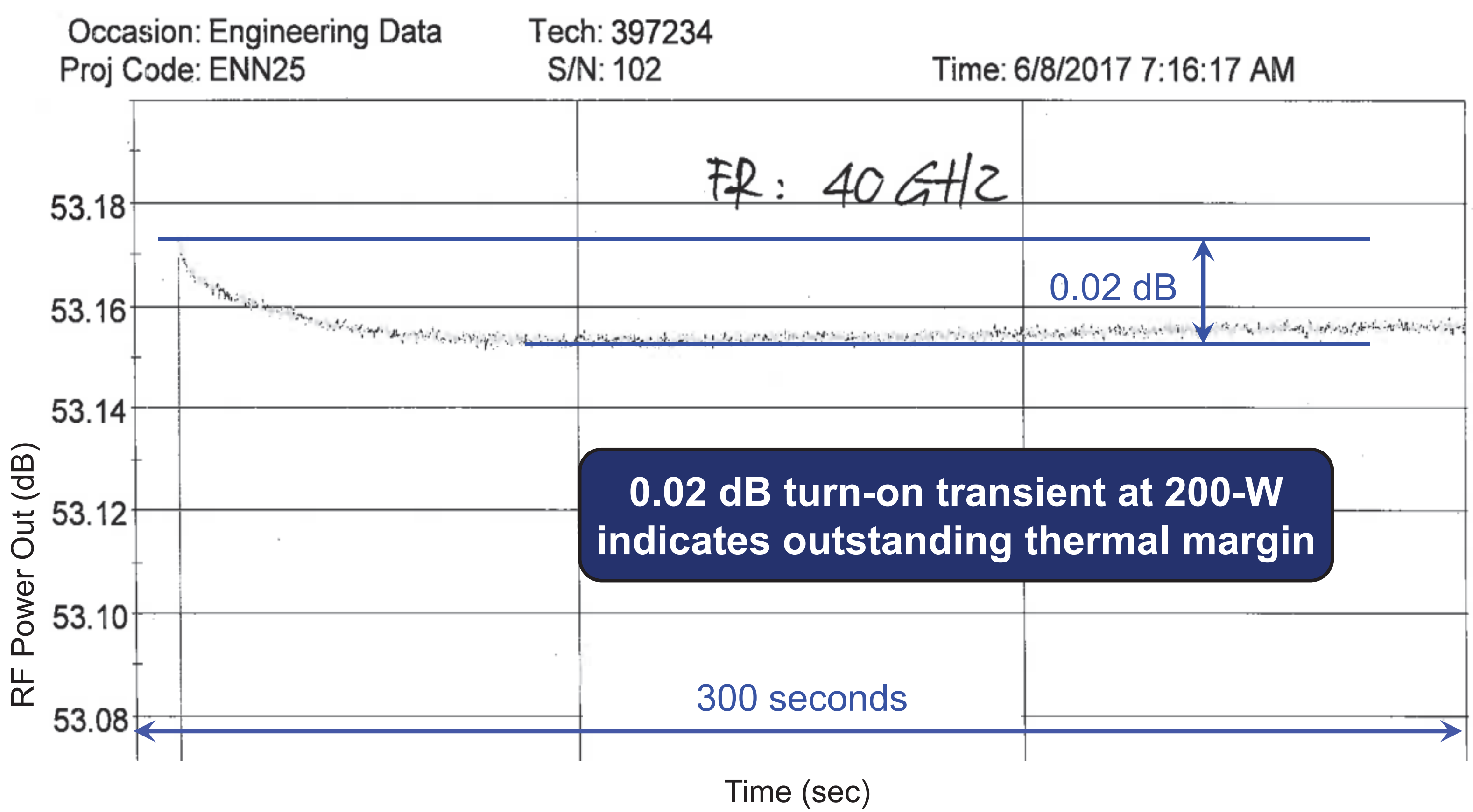
Frequency (GHz)	37.5	40.0	42.5	(No drive)
Drive Level		SAT		No Drive
Iw (mA)	0.51	0.57	0.64	0.12
Pin (dBm)	0.28	-1.25	-0.35	
Sat Pout (W)	203	207	200	
Sat Gain (dB)	52.8	54.4	53.4	
Total DC (W)	334	348	347	111
Thermal Diss (W)	132	141	146	111
Overall Eff (%)	60.7	59.4	57.8	
Phase Shift (deg)	-27	-41	-55	
AM-to-PM (deg/dB)	-2.6	-3.6	-5.2	
Gain Comp (dB)	7.7	7.7	7.5	
Noise Figure: 29 dB				

Broadband	5 Ghz
High Power	200-watts RF
High Efficiency	~60%
Typical Helix TWT performance	

Export Compliance Statement on Page 1

Model 9922H – Power Handling

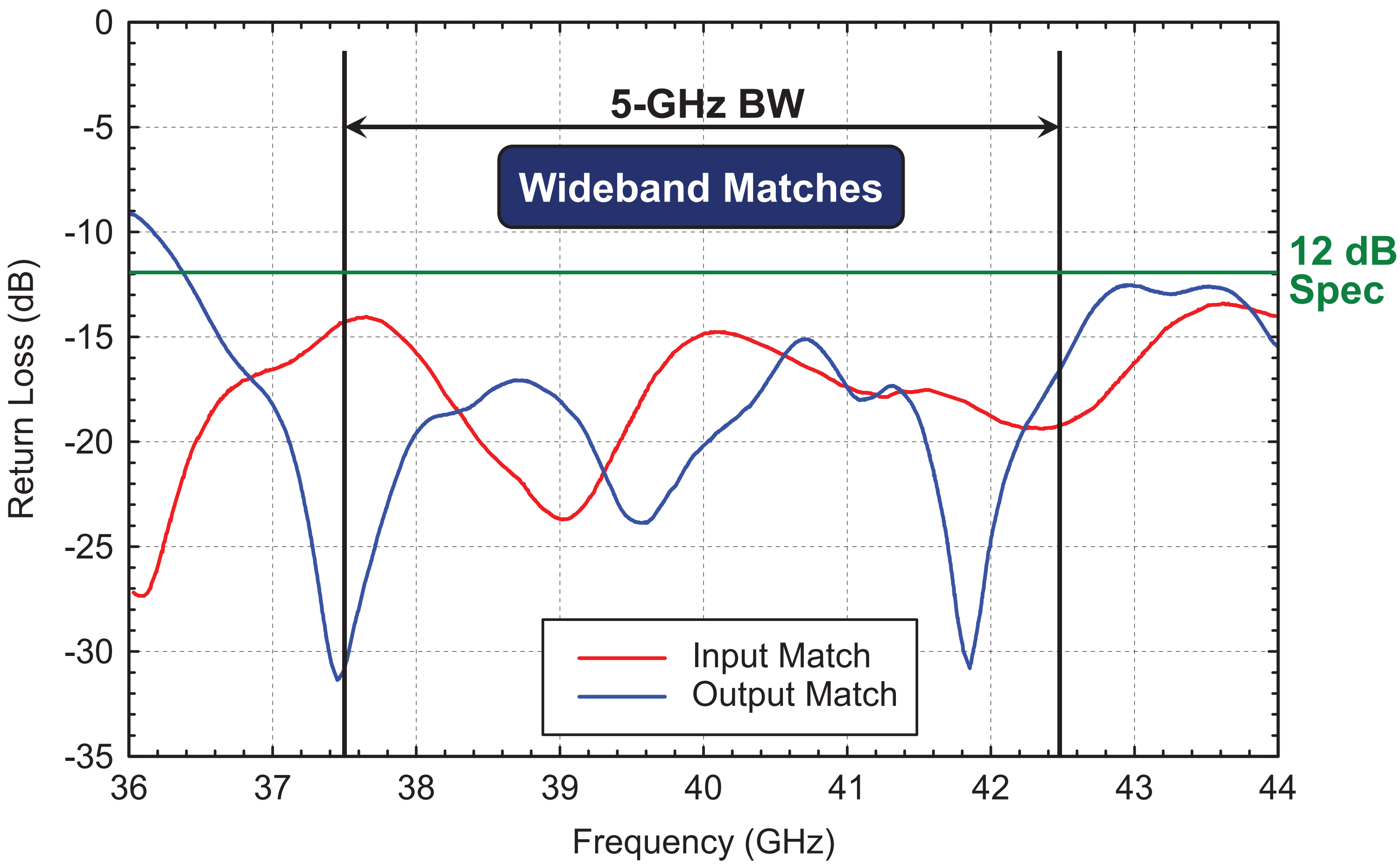
Electron Devices



Export Compliance Statement on Page 1

Model 9922H – Broadband Match

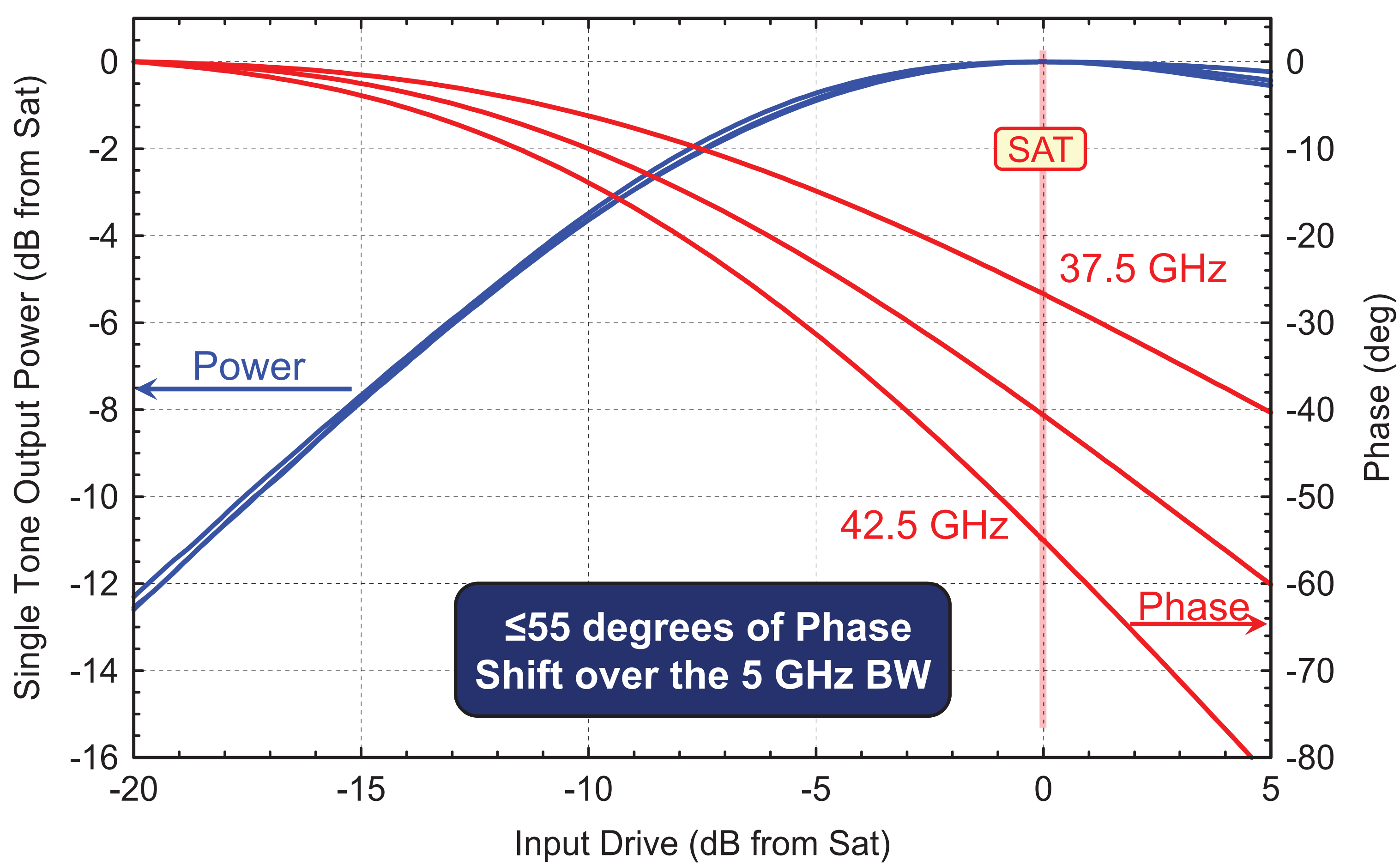
Electron Devices



Export Compliance Statement on Page 1

Model 9922H – Phase vs. Drive at 200 W

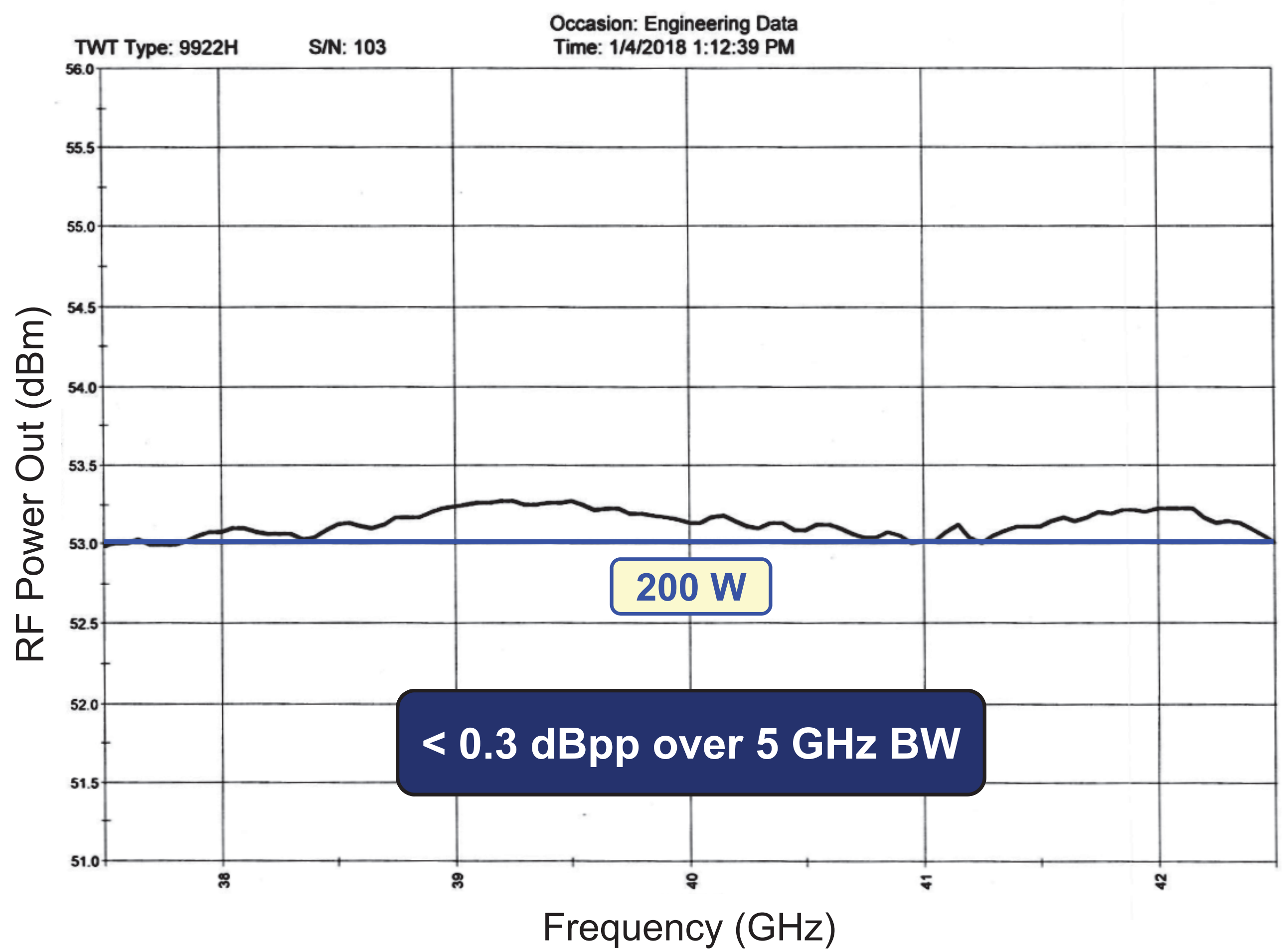
Electron Devices



Export Compliance Statement on Page 1

Model 9922H – Sat Power (Fixed Drive)

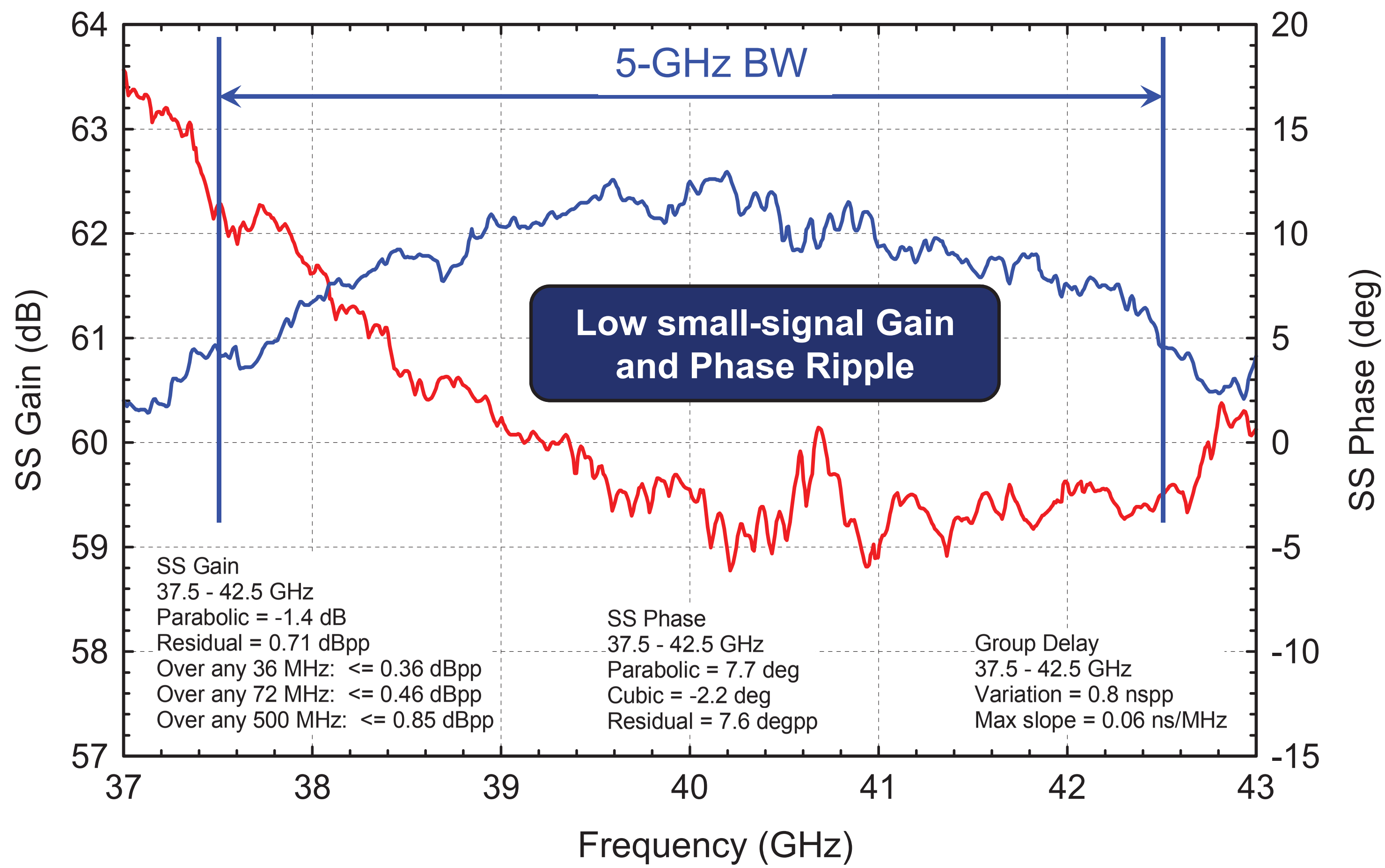
Electron Devices



Export Compliance Statement on Page 1

Model 9922H – Gain and Phase Sweep

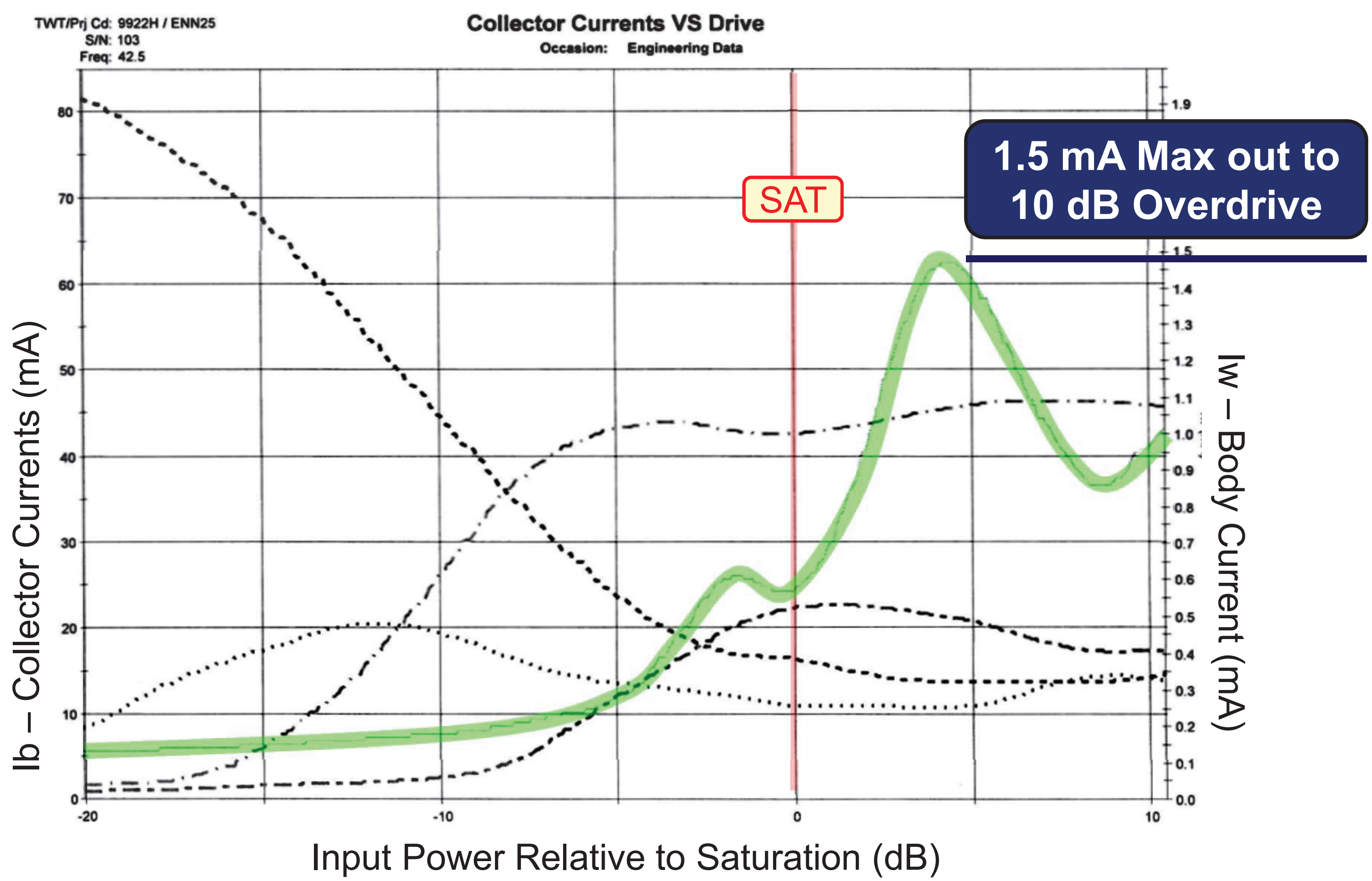
Electron Devices



Export Compliance Statement on Page 1

Model 9922H – Currents vs. Drive

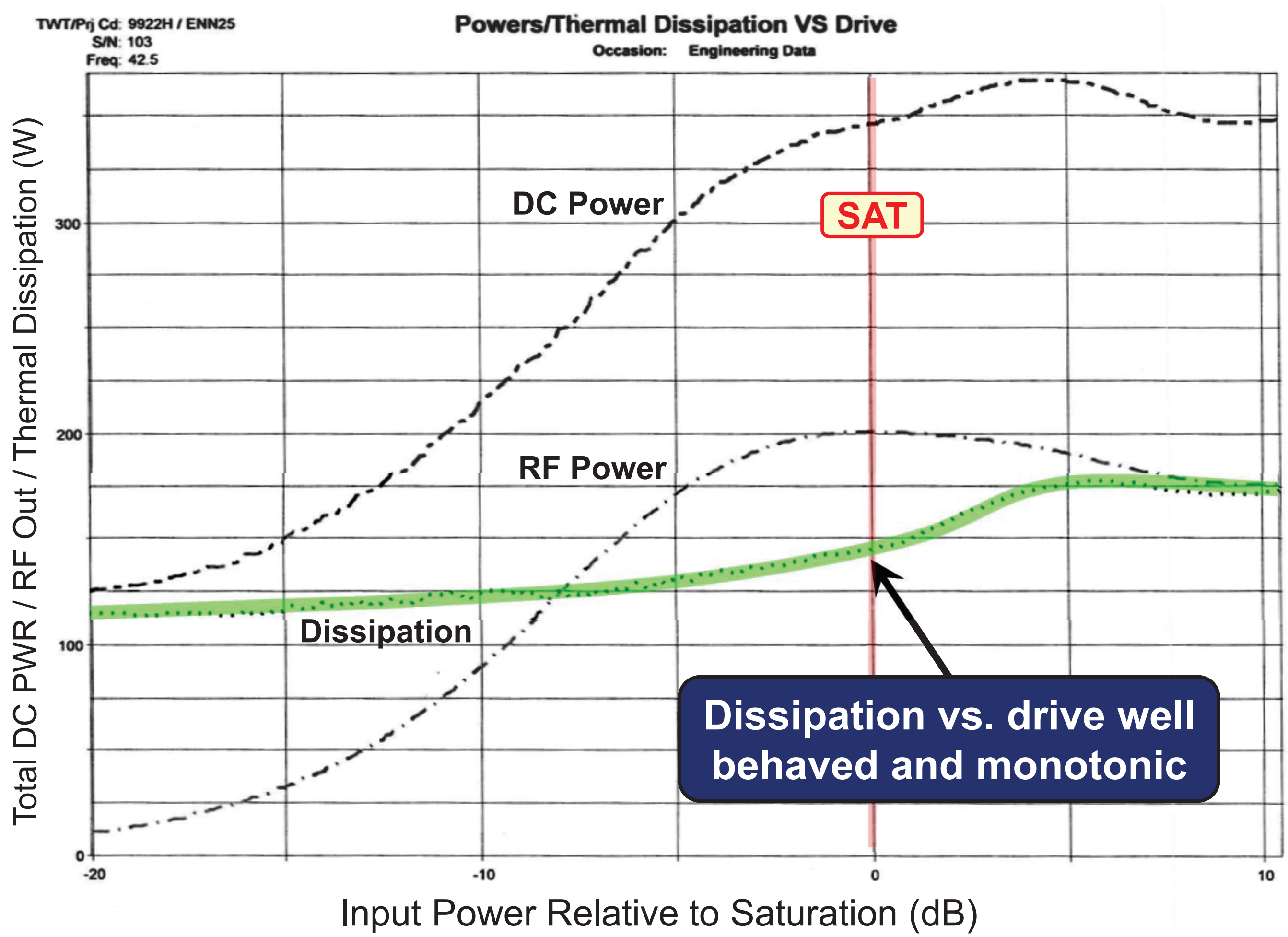
Electron Devices



Export Compliance Statement on Page 1

Model 9922H – Power & Diss. vs. Drive

Electron Devices



Export Compliance Statement on Page 1

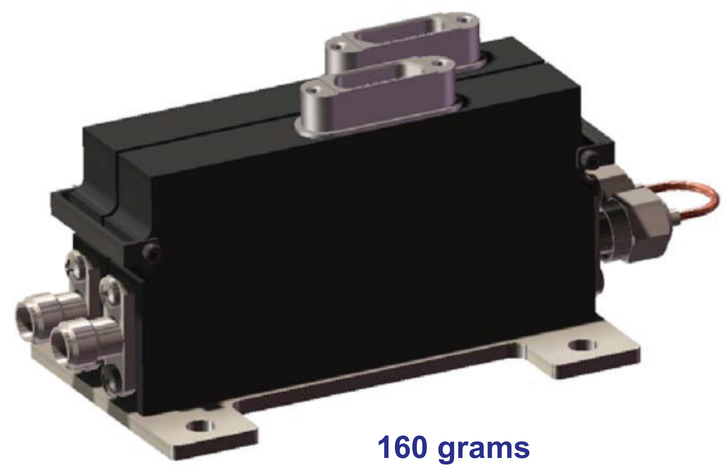
L3 Narda West Linearized Channel Amp

L3 Electron Devices

37.5 to 42.5 GHz Performance

Qualification tested -6° C to +63° C

- **CAMP**
  - Dual Mode: Fixed Gain & ALC
  - 36 dB Fixed Gain Adjustment, 1dB/step typical
  - Output Power Adjustment: 15 dB Minimum,18dB typical (0.5 dB Steps)
  - < 10 dB Noise Figure (@ step 0)
  - Temperature Compensated
  - Internal Band-Pass Filtering
  - Mass: <80 g
  - D.C. Power: < 4.0 W, typical
- **Linearizer**
  - 6 dB Typical Gain Enhancement
  - 45 Degrees Typical Phase Advance
  - Output Power Adjustment: 15 dB Minimum,18dB typical (0.5 dB Steps)
  - Mass: < 80 g
  - D.C. Power: < 2.5 W, typical



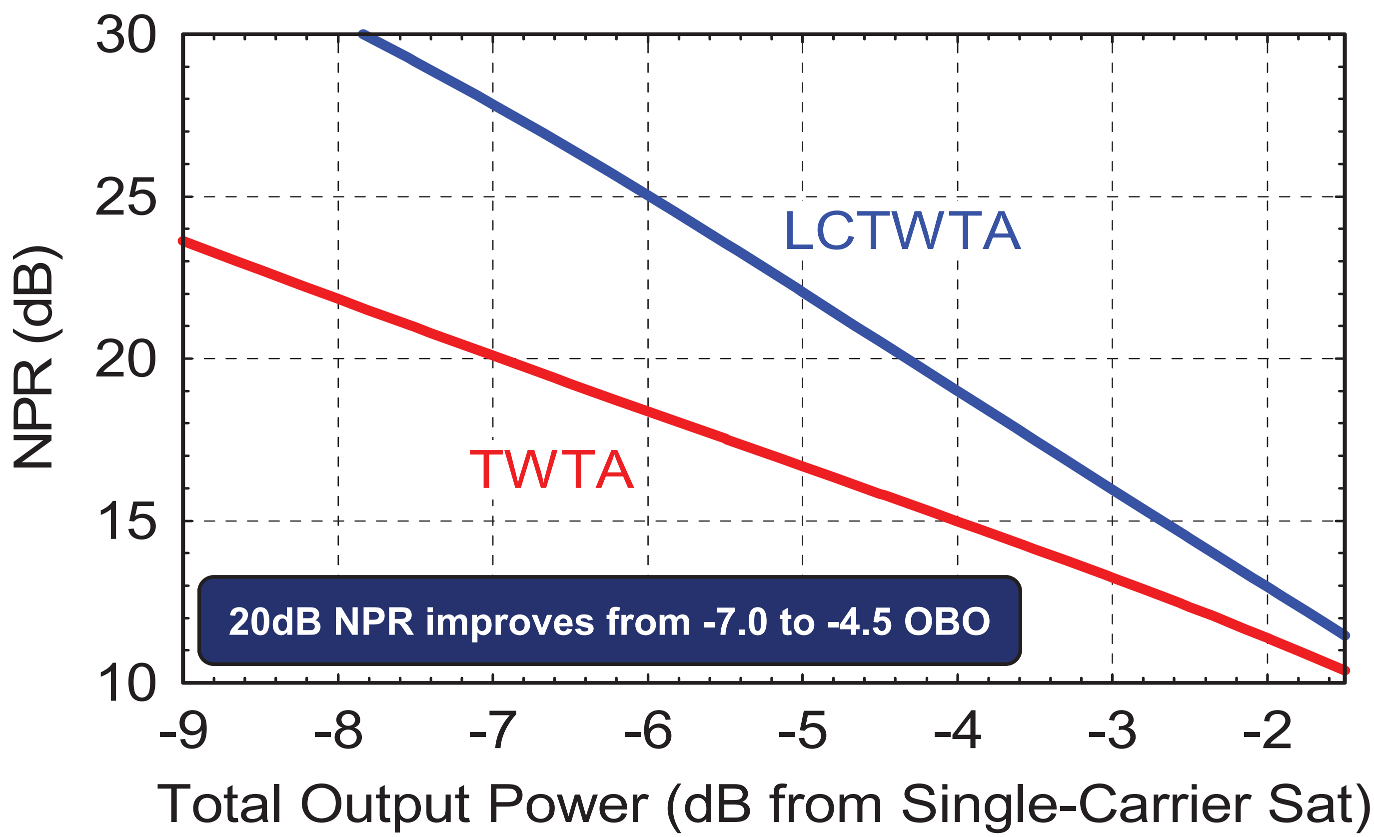
160 grams
Lightest Ever

Typical Lcamp performance now available at Q-band

Export Compliance Statement on Page 1

Q-band TWTA vs LTWTA – NPR Prediction

Electron Devices



Performance prediction for the L3 EDD Q-band TWTA
with and without the L3 Narda West Linearizer integrated

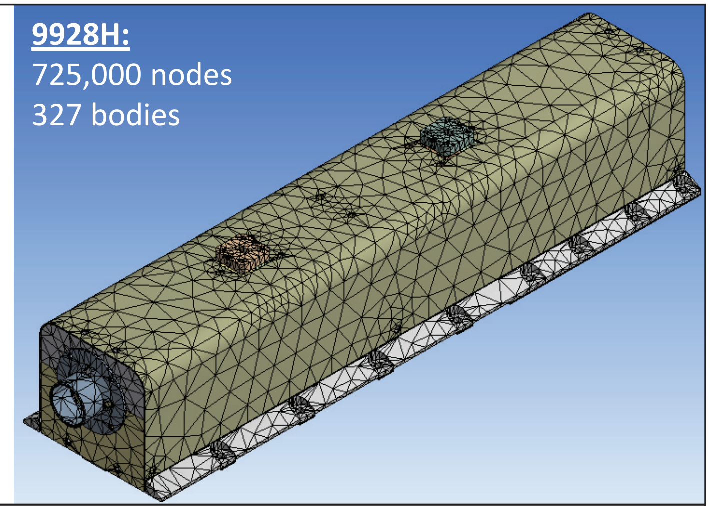
Export Compliance Statement on Page 1

Thermal Analysis: Results

When operating at 210-watts RF

Electron Devices

Location	Material	Temperatures (°C)						Min Margin at Location
		Allowable	No-Drive	Sat	6 dB IOD	10 dB IOD		
Internal Collector	Poco Graphite	*500**	215	162	153	147		285
Collector Exterior	Graphite Foil	*454**	164	138	137	134		290
Collector Cap	Solder	*173*	**154**	112	117	118		**19**
Collector Face	Magnet Epoxy	*339*	118	137	135	125		202
Feedthrough Solder	Solder	*173*	129	139	137	133		34
Output Waveguide	Aluminum	*300*	95	108	109	96		191
Output Circuit Barrel	Wet Stack Epoxy	*200*	99	129	130	106		70
Input Circuit Barrel	Wet Stack Epoxy	*200*	88	94	96	93		104
Circuit Trough	Solder	*173*	92	111	112	96		61
Input Waveguide	Aluminum	*300*	87	89	90	88		210
External Gun	Solder	*173*	94	96	97	96		76
Platform	--	--	85	85	85	85		
Minimum Margin at Drive:			19	34	36	40		

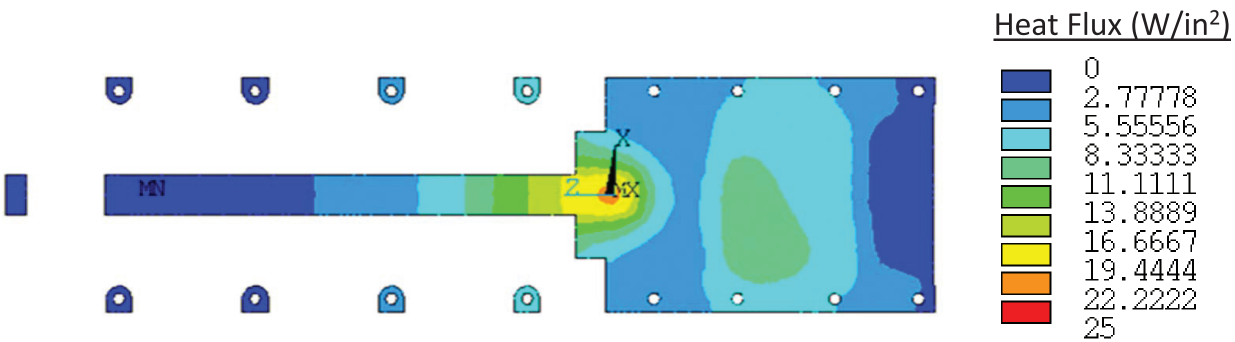


Lowest margin is 19°C at the collector end cap

@ Saturation

Overall Min = 0.7 W/in²

Overall Max = 20.0 W/in²



Predicted temperatures are below material and customer allowable limits

Export Compliance Statement on Page 1

Export Compliance Statement on Page 1

mm-Wave TWT Qualification Levels

Electron Devices

Qualification Test Event	Units	Ka-band	*Q-band	V-band
Random Vibration, X-Y Axis	Grms	19.4	17.9	15.4
Random Vibration, Z Axis	Grms	19.4	18.9	20.9
Shock, All Axes	G @ Hz	40g @ 100 Hz	70g @ 100 Hz	70g @ 100 Hz
Shock, All Axes	G @ KHz	2000g @ 1.0 KHz	1000g @ 0.8 KHz	1000g @ 1.4 KHz
Shock, All Axes	G @ KHz	2000g @ 4.0 KHz	2594g @ 3.0 KHz	2000g @ 4.0 KHz
Shock, All Axes	G @ KHz	2000g @ 10 KHz	2594g @ 10 KHz	2000g @ 10 KHz
Min, Operating Survival	Celsius (^{0}C)	-35	-35	-25
Min, Operating Performance	Celsius (^{0}C)	-25	-20	-15
Max, Operating Performance	Celsius (^{0}C)	75	90	70
Max, Operating Survival	Celsius (^{0}C)	75	90	70
Thermal Vacuum Cycles	# Cycles	9	16	28
Number of Units Tested	# Units	1 + 1 PFM	1 + 1 PFM	2

*Could argue that the Q-band TWT is qualified by similarity, but full qualification testing at 200-watts has now completed

Export Compliance Statement on Page 1

Sinusoidal Vibration

Electron Devices

This Qualification

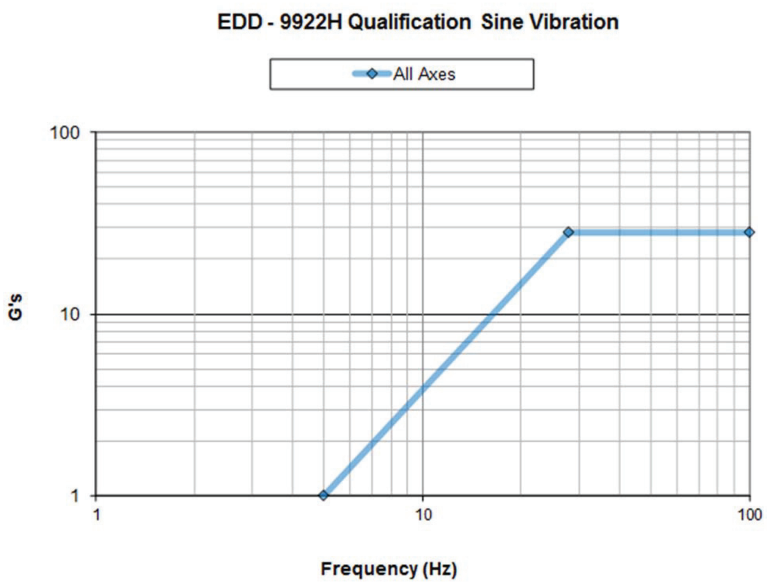
Q-band Qualification (All Axes)	
Sweep Rate: 2 oct/min	
Frequency (Hz)	Amplitude (G's)
5.0	1.0
28.0	28.0
100.0	28.0

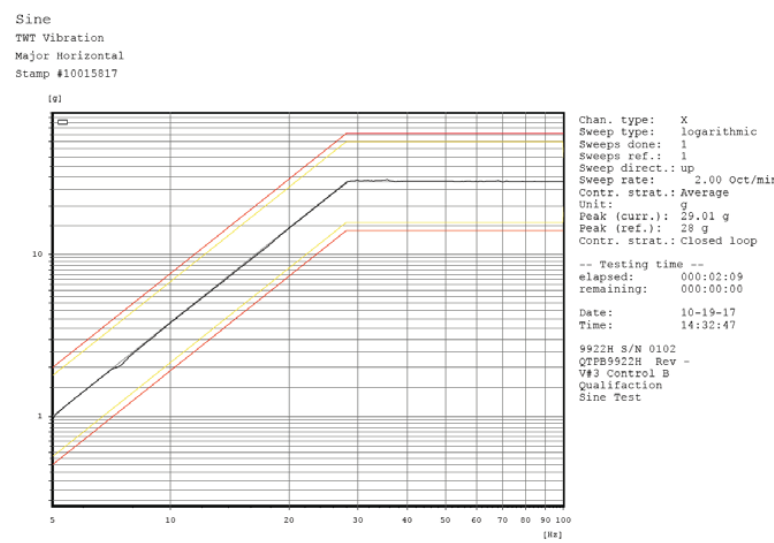
Heritage Requirements

Heritage mm-Wave (All Axes)	
Sweep Rate: 4 oct/min	
Frequency (Hz)	Amplitude (G's)
5.0	0.6
18.0	8.0
150.0	8.0

Current Production Spec

Q-band Flight Spec (All Axes)	
Sweep Rate: 2 oct/min	
Frequency (Hz)	Amplitude (G's)
5.0	0.60
22.6	13.0
50.0	13.0
51.0	5.2
100.0	5.2



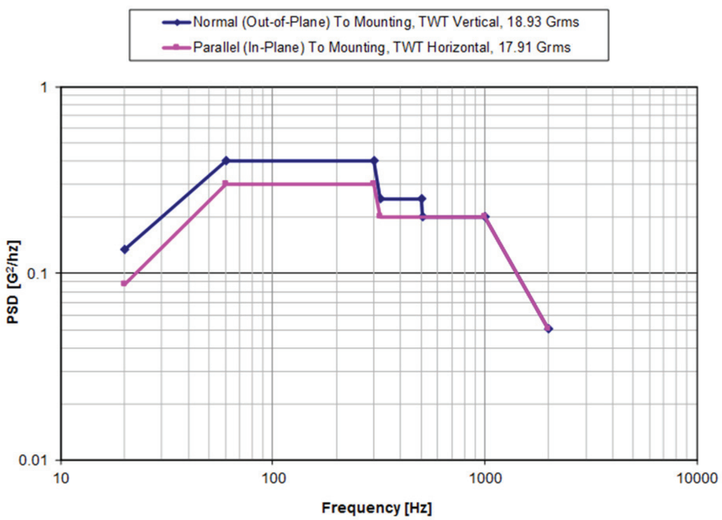


Q-band sine vibration test spec satisfies typical flight program requirements

Export Compliance Statement on Page 1

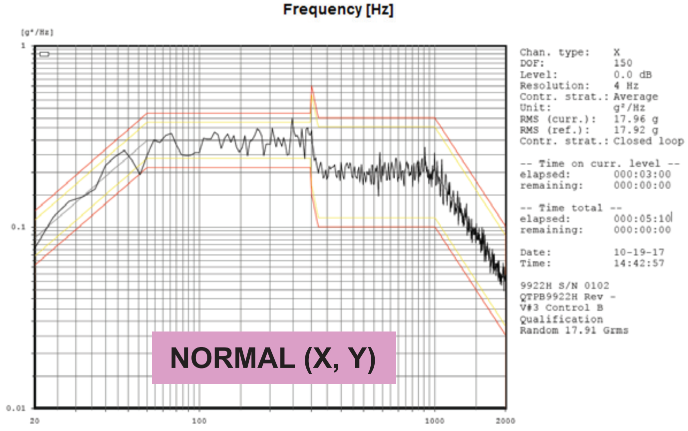
Random Vibration

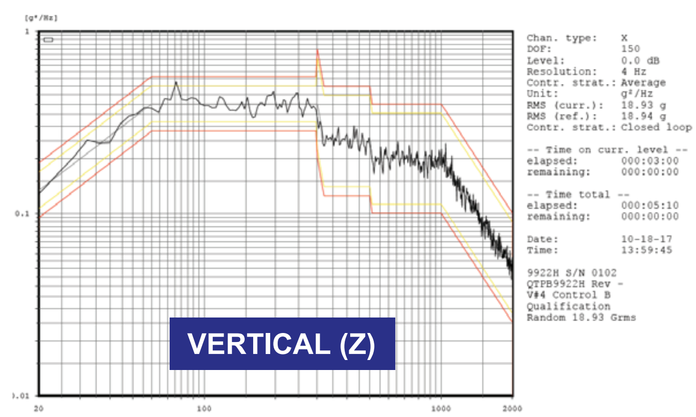
Electron Devices



RANDOM VIBRATION - QUALIFICATION LEVELS
180 sec/axis

TWT Axis	Frequency (Hz)	Power Spectral Density Beginning (G^2/Hz)	Power Spectral Density Ending (G^2/Hz)	Slope (dB/Oct)	Total (Grms)
Vertical (Z) Normal	20 - 60	0.1338	0.4000	3.00	18.93
	60 - 300	0.4000	0.4000	0.00	
	300 - 320	0.4000	0.2500	-21.92	
	320 - 500	0.2500	0.2500	0.00	
	500 - 510	0.2500	0.2000	-33.92	
	510 - 1000	0.2000	0.2000	0.00	
	1000 - 2000	0.2000	0.0502	-6.00	
Horizontal Major (X) & Minor (Y)	20 - 60	0.0867	0.3000	3.40	17.91
	60 - 300	0.3000	0.3000	0.00	
	300 - 320	0.3000	0.2000	-18.91	
	320 - 1000	0.2000	0.2000	0.00	
	1000 - 2000	0.2000	0.0502	-6.00	



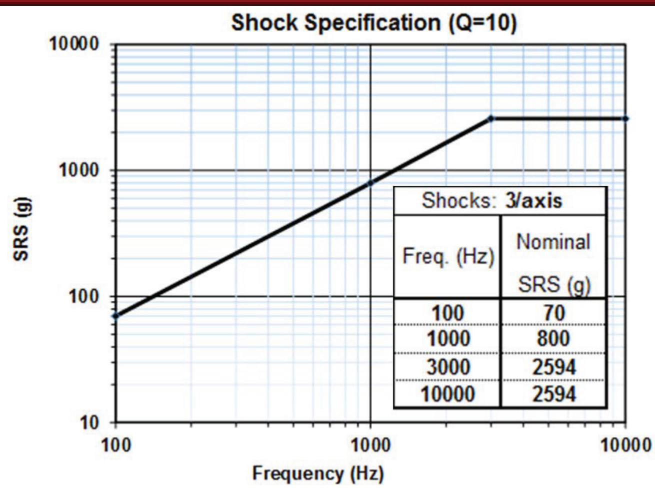


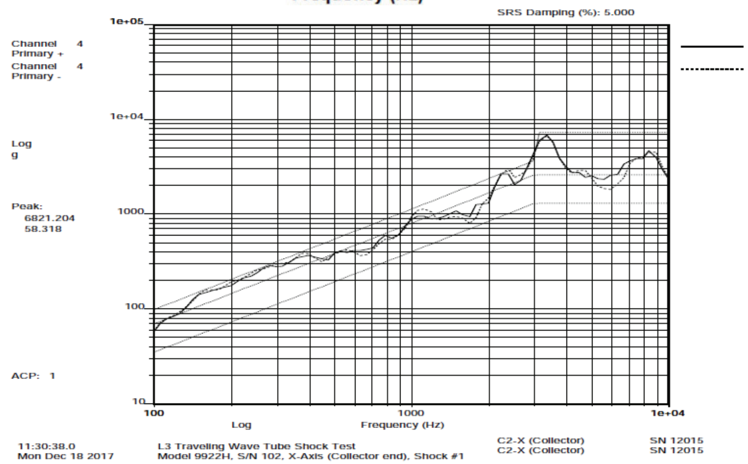
Q-band random vibration test satisfy typical flight program requirements

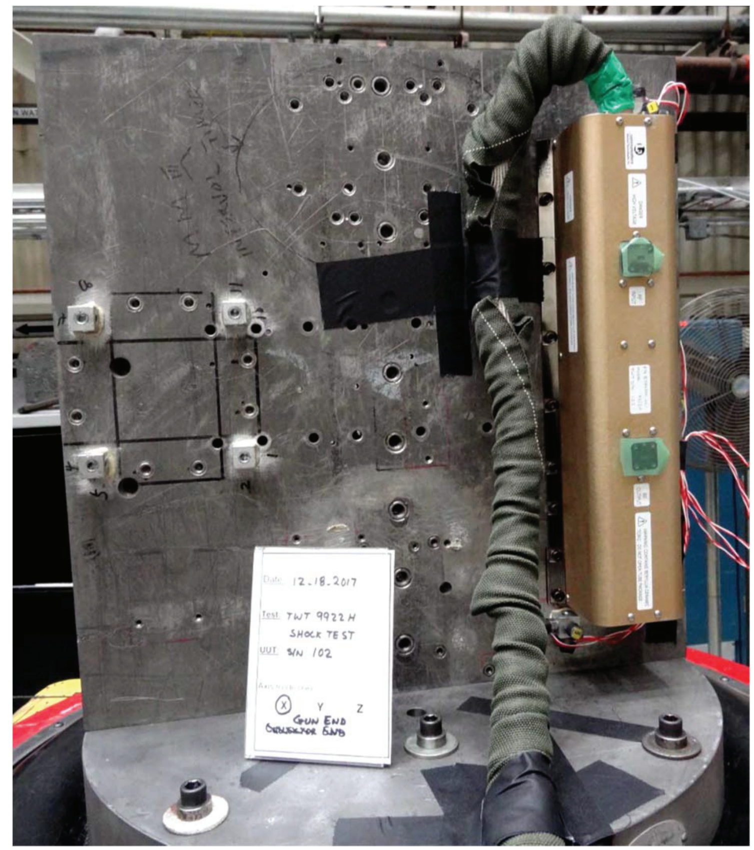
Export Compliance Statement on Page 1

Shock (X-Axis Example)

Electron Devices







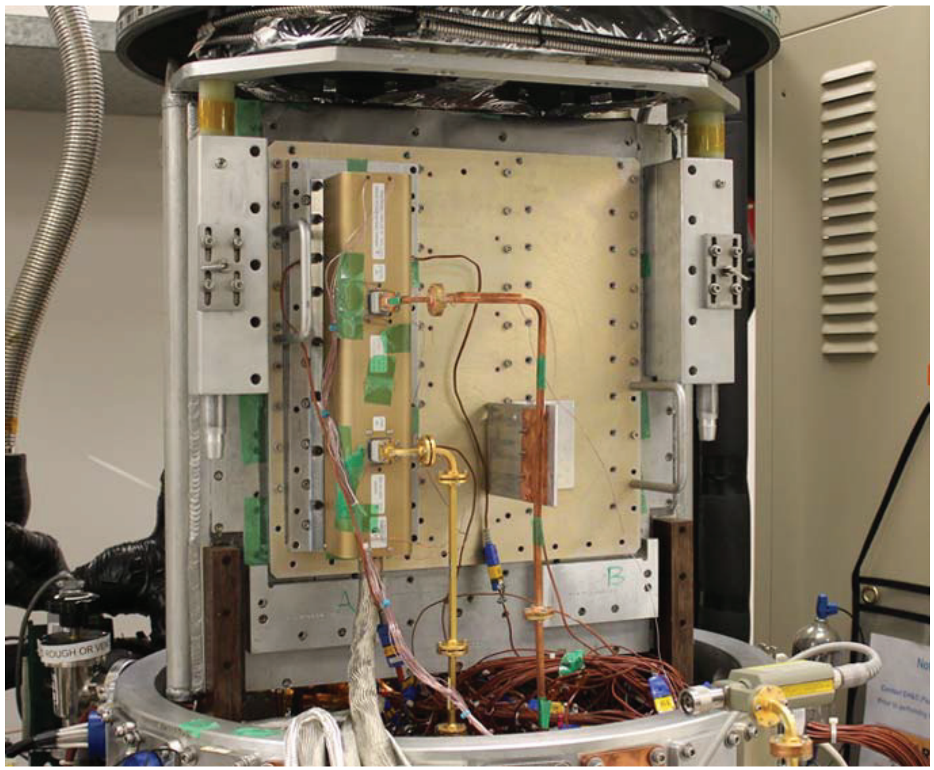
Q-band shock test satisfies typical flight program requirements

Export Compliance Statement on Page 1

Thermal Vacuum

Electron Devices

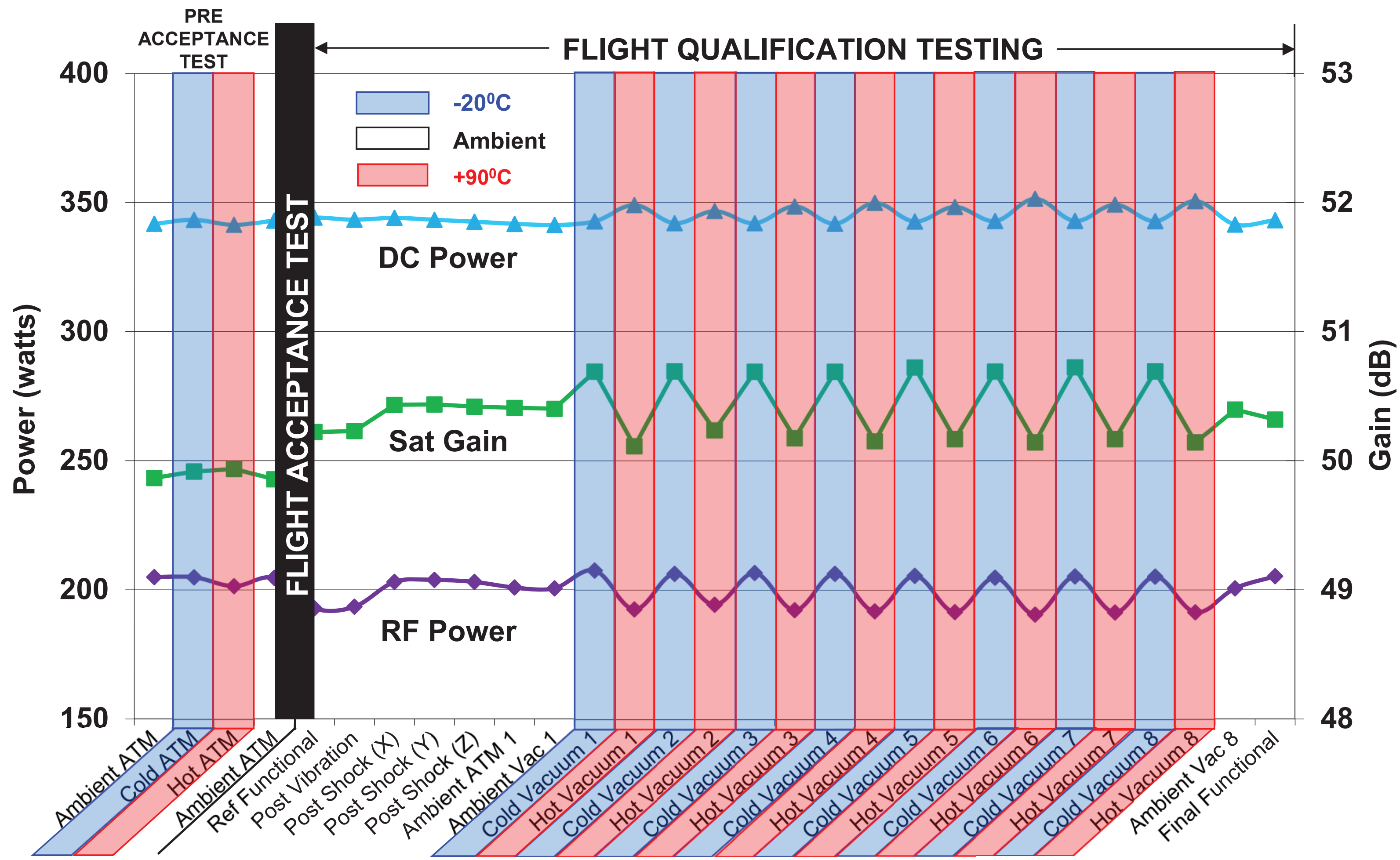
Source	Boundary	Operating (°C)		Non-operating(°C)		Start-up (°C)	
		Cold	Hot	Cold	Hot	Cold	Hot
EDD Q-band Qual Spec	Temperature (°C)	-20	90	-35	95	-35	90
	Cycles or starts	12 cycles		4 cycles		4 starts	4 starts



Export Compliance Statement on Page 1

Environmental Qualification Performance

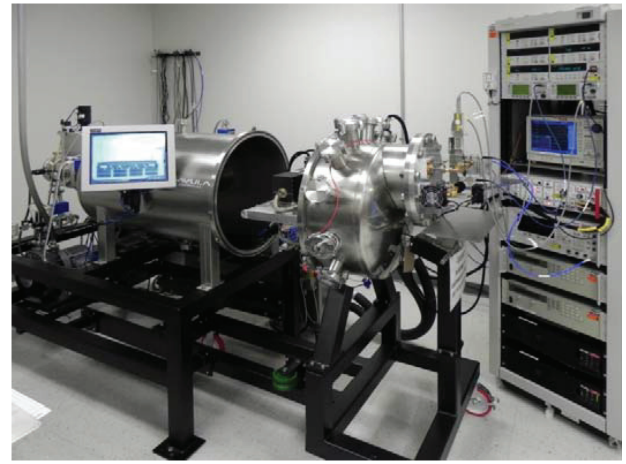
Electron Devices



Export Compliance Statement on Page 1

Life Test Experience

Electron Devices

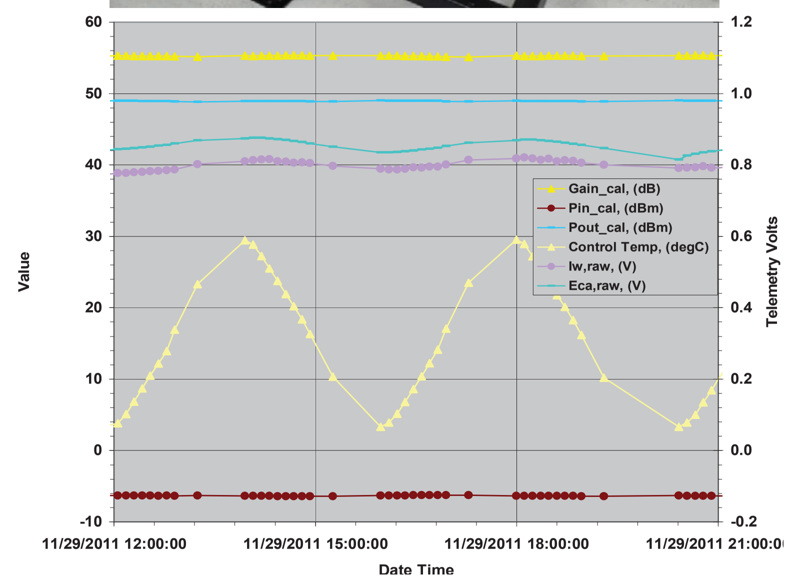


Model 1693HC TWTA:

- TWT Model 9915H
  - 58-64 GHz
  - 80-watts RF minimum
  - Operating at 13.5 kV

Performance thru April 16th, 2018:

- Testing began Nov 18th, 2011
- 22,805 operating hours
- 3,661 heater on/off cycles
- 406,523 HV on/off cycles
- 14,945 thermal cycles
- Entirely under vacuum
- No failures or anomalies



Export Compliance Statement on Page 1

Conclusion

- **The L3 EDD model 9922H Q-band TWT is now flight qualified at any RF power level up to 200-watts RF and over any portion or all of the 37.5 to 42.5 GHz frequency**
- **The L3 Narda West Q-band Linearizer & Channel Amplifier is now flight qualified over any portion or all of the 37.5 to 42.5 GHz frequency**
- **L3 EDD has a family of flight qualified and proven Electronic Power Supplies (EPC) capable of supplying voltage and processing DC power that supports any Q-band application of up to 200-watts RF**
- **Flight production of Q-band LCTWTAs has begun**

Export Compliance Statement on Page 1