Investigation and study on Cathode operating point of SPACE TWTs

Bijeev NV, Anju Malhotra, Vasant Jani, Virender Kumar, DK Singh, DK *Das*
Space Application Centre (SAC), Indian Space Research Organization (ISRO)
Satellite, Ahmedabad, Gujarat, India 380015
bijeev@sac.isro.gov.in, bijeev@rediffmail.com
Rajesh N Motta, SK Ghosh, Kanchi Prasad
D&E PS, Bharat Electronics Limited (BEL), Ministry Of Defense (MOD)
Bengaluru, Karnataka, India
rajeshnmotta@bel.co.in

Abstract—*Microwave tubes are used in for RF signal amplification in terrestrial and for space applications, especially in cases where high RF power levels of several ten watts or higher are needed.*

I. INTRODUCTION8

Travelling Wave Tube Amplifiers (TWTA's) are commonly used for satellite communication links, earth observation payloads, scientific missions or probes, inter-spacecraft communications links etc. Especially telecommunication satellites are equipped with a large number of TWT's. The TWTA is formed by the Electronic Power Conditioner (EPC) and the Travelling Wave Tube (TWT). The TWT is an electron transport device and used to offer RF power of 30W to 300W for typical space applications in the L, S, C, Ku, Ka, Q and V Band frequency range. The efficiency of a TWT is up to the 70 % range and that of EPC is above 90%. Due to the overall efficiency above 60% makes TWTA the right choice over its counterpart solid state power amplifiers for typical satellite applications. Due to the large numbers of such devices on telecommunication satellites, their dimensions, mass, and efficiency are major contributors to the satellites power budgets and therefore require special attention.

II. Travelling Wave Tube Amplifier (TWTAs)

The basic components of a Travelling Wave Tube (TWT) are shown below. The electron gun contains the cathode for electron emission and forms an electron beam. The beam is feed through the helix slow wave structure, whichcouple the electromagnetic field of the electrons with the signal fed into the input of the helix (RF input). The interactions between electron beam and RF signal on the helix cause signal amplification, so high RF power signal can be coupled at the RF output. Subsequently electron beam is collected in the collector stage, consisting of typically 4 collectors. The cathode voltage is the most negative voltage with reference to the helix, which will be at chassis ground.Typical cathode voltage of space TWT will be in the range of 3-8KV depending on operating frequency of TWT. The collector voltages are a fraction of the cathode voltage

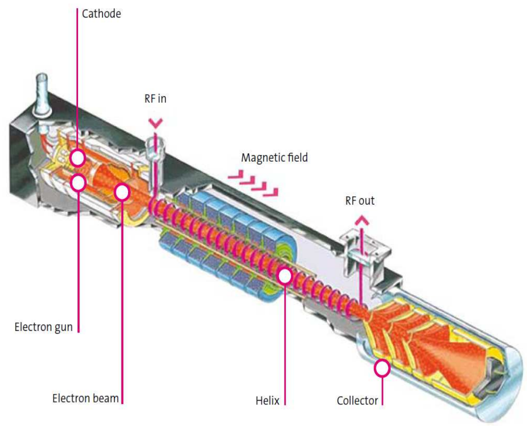


Fig. Cross section of TWT

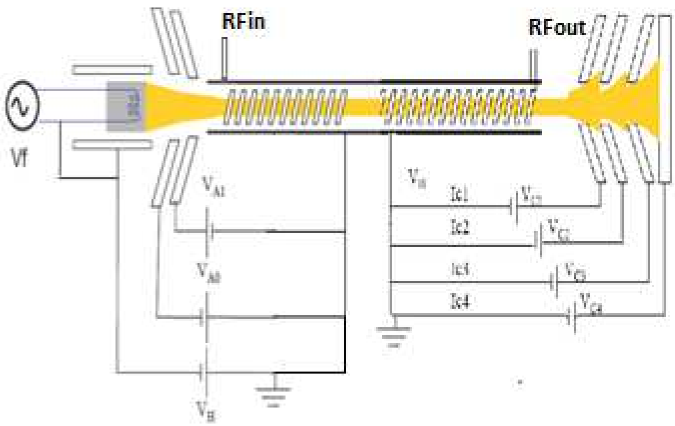


Fig. TWTA, EPC-TWT interface diagram

The voltage VF is needed to heat the cathode filament to allow emission. The anode voltages VA1 needed for ion control inside tube whereas VA0 needed to accelerate electrons from the cathode and to form the beam. The emission current is mainly depending on the voltage VA0 and a specific constant called pervience of gun, μ. Acceleration of the electrons is determined by the helix voltage VH.The TWT interface consists of the collector voltage C1,C2,C3,C4 and eventually C5, the cathode voltage K, the Wehnelt W and the anode voltage A0, the filament heater voltage F to FK, the anode voltage A and the helix voltage H. The filament converter is then generating the necessary AC supply voltage for the TWT filament heating. The filament heater low voltage is floating on the high voltage potential of the cathode. A soft start is implemented for the filament converter to avoid surge currents when the tube filament is cold and has then a lower resistance**.**Generally, the EPC provides a number of very stable high voltage outputs required by the TWT. It generates these outputs from a more or less stable main bus voltage. Typically output voltages needed are the following:

- Helix Voltage
- Cathode Voltage
- Collector Voltages (typically 4 collectors)
- Heater Voltage (Low voltage floating on cathode potential)

In order to have a stable RF performance, the TWT requires these voltages to be very stable vs. temperature, load, and life of the unit, as well as practically free of ripples. The EPC generates these high voltages out of a bus voltage of typically unregulated 26-42V or semi-regulated 70V Bus. The helix voltage is up to approximately 6200V (for typical Ku-Band tubes) and should be stable within 1V for any output power level respectively within some 10V vs. temperature and 15 years of life in orbit. The voltage ripple on cathode voltage shall be less than 0.3V.

III. STUDY ONCATHODE OPERATING POINT DURING INEVSTIGATION ON FM1 TWTA

Indigenously developed 60W C-BAND TWTA(FM1) was undergoing investigation due to output power variation observation during thermal cycling test. During the first thermal cycling test on FM1, it was observed that the RF output power was degraded from 65W to 20W when EPC base plate temperature was elevated above +44C. However from +44 C to -15C, TWTA was delivering constant RF power around 65W. Though, it was expected to have some variations in RF output power due to filament voltage temperature regulation (< +/-50mV), RF out power variations in the order of 40W was never expected. The Knee characteristic of cathode was suspected to be the contributing to this huge variation in output power with temperature.

Observation of reducing input dc current and output power during thermal cycle of FM1 TWTA

Input voltage (43 V)	DC I_{in} (A)	ARO	HRO	CH+	CH-	Temp (°C) TWT base plate	Temp (°C) EPC base plate	Shroud Temp (°C)
LV ON	0.21	-	-	6.351	6.573	24	23	22
HV ON	2.58	0.906	0.965	6.362	6.583	25	23	22
HV ON	1.82	0.906	1.042	6.362	6.583	41	50	22
HV ON	1.71	0.906	1	6.362	6.583	46	54	35
HV ON	1.65	0.906	1.306	6.362	6.583	47	56	45
HV ON	1.15	0.906	1.23	6.362	6.583	57	60	58
HV ON	1.08	0.906	1.165	6.362	6.583	57	61	49

The investigation carried out on FM1 TWT in following steps.

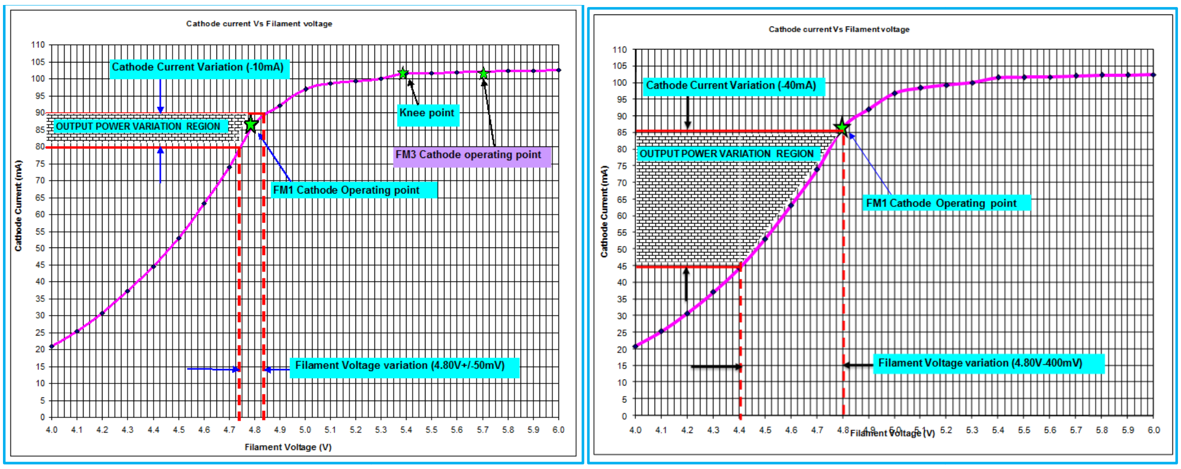
1) *Sensitivity Analysis/Measurements:* TWT de-integrated from EPC and connected to HV Lab power supply. To quantify the output power degradation with filament voltage, a sensitivity analysis and measurement performed on the TWT with APKONHV Lab power supply. The filament voltage in HV power supply was changed to +50mV and -50mV from nominal value of 4.8V and observed the RF output power of TWT. The observations were tabulated as below.

FM1-TWT-Pout variation w.r.to filament voltage when tested with APKON Power Supply

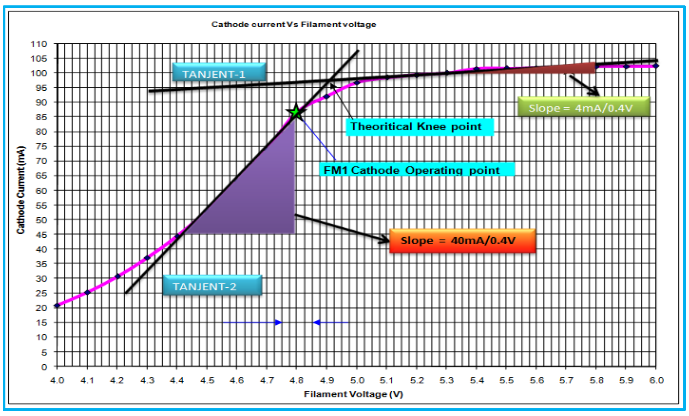
Case	Vf (Filament)	Vk (Cathode)	Pout(saturation)							
			3905 MHz	3925 MHz	3945 MHz	3965 MHz	3985 MHz	4005 MHz	4025 MHz	Observation/Remarks
2	4.75V	3138V	61.7W	56.3W	52.4W	52W	55.3W	60W	63.9W	Average Pout variation is 14.7 W and Pout increases with Filament voltage in all frequencies & cases
5	4.80V	3138V	68W	63.5W	59.8W	59W	62.3W	68W	72W	
8	4.85V	3138V	75.3W	70W	66.5W	66W	70W	76.5W	80W	
Delta Pout-TWTA			+13.7W	+13.7W	+14.1W	+14W	+14.7W	+16.5W	+16.1W	

2) *Knee characteristics measurement:* To confirm that whether FM1 TWT cathode operating point is kept above or below the knee point, the filament voltage verses cathode current plot was made after measurements with APKON power supply.

Cathode Knee-Curve of FM1 TWT when tested with APKON Power supply



3) *Assessment by mathematical calculation from the graph*



Output power variation w.r.to cathode current variation above the Knee Point, is related as equation.

$$\Delta P_{OUT} = P_{OUT-NOMINAL} \cdot \frac{4}{3} \cdot \frac{\Delta I_K}{I_{K-NOMINAL}} = 75W \cdot \frac{4}{3} \cdot \frac{10mA}{85mA} = 12W.approx.$$

ie for 10mA change in cathode current can lead to approximately 12W reduction in TWT output power above Knee point.Also the filament voltage is not only the sole reason which can change in cathode current. It can be due to cathode voltage and control anode voltage. The present design does not have control anode (only Ion barrier anode and it hardly influence the cathode current as it is placed far away from the cathode) and hence the cathode current variations can be ruled out. Also EPC level data says there is no change in Ion barrier anode voltages with temperature. The cathode current variations due to cathode voltage can be quantified as follows

$$\Delta I_K = I_K.\frac{3}{2}.\frac{\Delta V_K}{V_{K-NOMINAL}} = 85mA.\frac{3}{2}.\frac{10V}{3138V} = 1mA.approx.$$

This so negligible and can be neglected. Worst-case helix change w.r.to temp is 10V in above calculation.

There is also a change in small signal gain of TWT when the cathode current changes. The following equation shows how it is related each other. However, in our case we were saturating the TWTA to get the maximum power in the anomalous condition and hence it can be ignored.

$$\Delta G_{SS} = BCN.\frac{1}{3}.\frac{\Delta I_K}{I_{K-NOMINAL}}$$ Where BCN is electronic gain of TWT

Investigation carried out on subsequent FM3 TWTA as follows. FM3 TWTA Tested in ambient temperature first for Filament voltage sensitivity analysis. The results are below.

FM3-TWT Pout variations when tested with APKON Power Supply

Case	Vf	Vk	Pout(saturation)							
			3865 MHz	3885 MHz	3905 MHz	3925 MHz	3945 MHz	3965 MHz	3985 MHz	Observation/Remarks
2	5.59V	3134V	78.1W	78.5W	78 W	79W	80.5W	82.8W	83W	Average Pout variation is 5W but Pout decreases with Filament voltage increase at some frequencies
5	5.64V	3134V	81W	86W	87W	84W	79W	75.5W	77.5W	
8	5.69V	3134V	82W	87W	87.5W	85W	80W	78W	78.5W	
Delta Pout			+3.9W	+8.5W	+9.5W	+6W	+0.5W	-4.8W	-4.5W	

Subsequently FM3 TWTA was subjected to thermal Cycling in the specified acceptance level temperature in three configurations to understand the FM1 TWT phenomena.

- EPC inside Thermal chamber and TWT outside.
- TWT inside Thermal Chamber and EPC outside
- Both EPC & TWT; i.e. TWTA inside chamber

Case – I: EPC inside and TWT outside chamber

EPC Base Plate Temp °C	TWT Base Plate Gun side Temp °C	TWT Base Plate Coll side Temp °C	TWT Base Plate Coll top Temp °C	DC Iin (A)	Vf (V)	Pin (dBm)	Pout (dBm)
23	-	-	-	2.74	5.555	-	-
23	-	-	-	3.91	5.555	-0.8	48.7
63	-	-	-	3.19	5.392	-0.8	47.38
-16	-	-	-	4.05	5.572	-0.8	48.71

Case – II: TWT inside and EPC outside chamber

EPC Base Plate Temp °C	TWT Base Plate Gun side Temp °C	TWT Base Plate Coll side Temp °C	TWT Base Plate Coll top Temp °C	DC Iin (A)	Vf (V)	Pin (dBm)	Pout (dBm)
-	23	23	23	2.64	5.554		-
-	23	23	23	3.96	5.554	-0.8	48.47
-	65	81	88	4.11	5.499	-0.8	48.54
-	-15	-3	0	4.11	5.51	-0.8	48.00
-	-22	-8	-4	3.31	5.515	-0.8	47.86

CASE-III Entire TWTA inside chamber

EPC Base Plate Temp ^{0}C	TWT Base Plate Gun side Temp ^{0}C	TWT Base Plate Coll side Temp ^{0}C	TWT Base Plate Coll top Temp ^{0}C	DC Iin (A)	Vf (V)	Pin (dBm)	Pout (dBm)
23	23	23	23	2.85	5.576	-	-
23	23	23	34	4.23	5.576	-2.3	48.58
30	37	45	56	4.19	5.537	-2.3	48.36
35	43	53	65	4.18	5.516	-2.3	48.27
40	47	61	69	4.16	5.509	-2.3	48.14
45	51	70	74	4.16	5.496	-2.3	48.53
50	56	79	81	4.16	5.476	-2.3	48.51
55	60	81	85	4.16	5.450	-2.3	48.48
60	63	82	85	4.11	5.429	-2.3	48.39
62	65	83	90	4.09	5.421	-2.3	48.37
0	-3	10	17	4.24	5.564	-2.3	48.64
-5	-9	3	9	4.24	5.592	-2.3	48.69
-10	-15	-2	1	4.15	5.605	-2.3	48.67
-15	-22	-7	-4	4.13	5.605	-2.3	48.63

Observation on FM3 TWTA: Unlike FM1 TWTA, output power of FM3 TWTA remained constant within 0.5dBm power variations, during thermal cycling. This was indicative of the fact that FM3 TWTA cathode operating is above knee point.

Re-optimization of FM1 TWT for better cathode operating point, required output power and bandwidth: After attributing the anomalous behavior of FM1 TWT on a faulty cathode operating point of TWT, it was decided to re-optimize FM1 TWT for cathode operating point and bandwidth, output power and helix current performances. The FM1 TWTA was envisaged to be used in CH#6 (3925 MHz) & CH#7 (3965 MHz) of ISRO's communication payload. TWTA has to deliver 60W of minimum RF output in the operational bandwidth of 300MHz with minimum helix current. Experiments performed on FM1 with HV lab power supply, to achieve this goal. The following table shows the result.

During the test of FM1 TWT with Lab power supply in the present cathode operating point (VF=4.80V), it was observed that the helix current was slightly high (6-7mA) compared to the QM TWT (3-4mA) manufactured earlier. So measurement were performed on FM1 TWT, by playing with the filament and cathode voltages to locate a better operating point such that the required RF output power will be available throughout the required 300MHz bandwidth with optimum helix current. But after so many iterations also, TWT was not able to deliver 60W power throughout the required bandwidth of 300MHz with reduced helix current.Subsequently, explored the possibility of optimizing the FM1 TWT further for a reduced bandwidth of 120MHz (+/-60MHz around center frequency 3965MHz) to locate a better efficient operating point with optimum helix current. The best operating point was arrived at after so many iterations of filament and cathode voltage levels as shown in table 1. The optimized FM1 TWT was delivering 60W output power in the required band with less than 1.8mA helix current

Table. FM1 TWT with Lab Power Supply (F= 3.965 GHz +/- 60 MHz, Vf 4.842 V, V0 = -3138 V)

Freq	Pout (W)	Pin (dBm)	I-helix (mA)
3,905	60	-8,9	1,4
3,925	60	-7,3	1,4
3,945	60	-5	1,6
3,965	60	-6,4	1,8
3,985	60	-6,3	1,6
4,005	60	-7,2	1,6
4,025	60	-8,4	1,7

Table. FM1 TWT with EPC (F= 3.965 GHz +/- 60 MHz, Vf =4.83 V, V0 = -3138 V)

Frequency	Pout (W)	Pin (dBm)	I-helix (mA)
3,905	60	-8,3	1,6
3,925	60	-6,4	1,72
3,945	60	-4	2,11
3,965	59	-2,9	2,87
3,985	60	-4,4	1,93
4,005	60	-6	1,71
4,025	60	-7,5	1,6

This operating point is considered as an optimum one as it gives required power throughout the band with minimum helix current and almost constant gain (Nominal +/- 2 dB) which is commonly achievable by a non-linearized TWT. However during the testing of FM1 TWT with FM EPC with almost same voltage settings as optimized with Lab power supply, the measured RF output power and helix current were found slightly different from the corresponding values with that of Lab power supply as per table 2.an observation that the RF output power and Helix current are very sensitive to Filament voltage changes. so there arise a concern that the cathode operating point may be near or below Knee point of its emission characteristic, where, the cathode current will be more sensitive to cathode temperature and there by filament voltage. The EPC filament voltage is expected to have variations with temperature (1% temp regulation). And also for a long life operation of TWT, this temperature-limited region of cathode is not preferred, as the cathode current varies with filament voltage variations and hence the output power. The suitable cathode operating point shall be above knee point, ie space charge limited region, where the cathode current is more or less constant with filament voltage variations

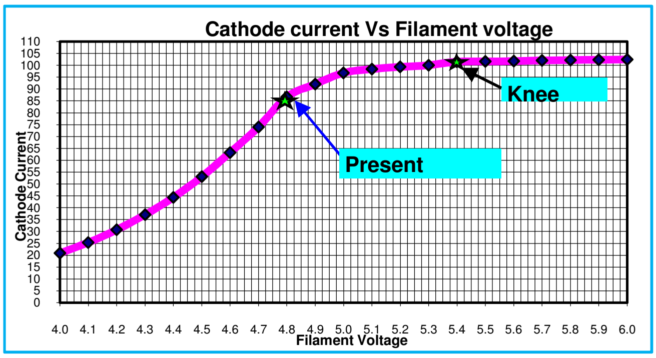


Table FM1 TWT with Lab Power Supply

Freq (GHz)	Po (sat) W	Pin (dBm)	I-helix (mA)
3.905	70.0	-4.0	6.0
3.925	65.8	-4.0	5.2
3.945	64.5	-5.0	6.2
3.965	67.8	-5.0	6.5
3.985	73.0	-5.0	7.5
4.005	78.9	-5.0	7.8
4.025	80.0	-4.0	7.0

Fig.1 Measurement of cathode current verses filament voltage

5.4V may be considered as knee point as the cathode current is almost constant (102mA) there onwards if you see the plot of fig.1. So RF measurement performed again at filament voltage of 5.4V, which is above Knee point and can give more appropriate cathode operating point for long life cathode with more stable TWT output power.The measurement results are as follows

Test Conditions:
Vf = 5.4 V, Vk = -3100 V,Collector voltages remain same as in EPC, Cathode current 98.3 mA

However, during the measurement, the observation made was that the helix current is too high at this operating point of 5.4V and hence the efficiency of TWT is going to be suffered at a large amount. One of the reasons for this was analysed as the TWT is operated at a high cathode current of 102mA, above knee point, when the required cathode current was only 80mA, which need to be above knee point.

Then it is recommended to explore the possibility of shifting the operating point of cathode in such a way that above the Knee point the cathode current is only 80mA. Three options were there to do this exercise

- By changing the Beam Forming Electrode (BFE) voltage
- By changing the control Anode voltage
- By changing the Cathode voltage

The options a & b were not available with the present C-band design as the BFE is at cathode potential and also the anode is an Ion Barrier Anode, which does not have so much influence on cathode current. So the third option was only available to us to explore. By reducing the cathode voltage it is expected that the cathode current will saturate at a lower value above knee point to the required 80mA instead of the present 102mA. This can set the operating point above knee point as 80mA, provided that, the required power of 60W shall be available at slightly lower cathode voltage also. These measurements were carried at BEL, Bangalore following are the results. The DC measurements have shown improvements in the cathode characteristics, i.e. reduced the saturated cathode current above knee point, towards the required 80mA as per the fig.2

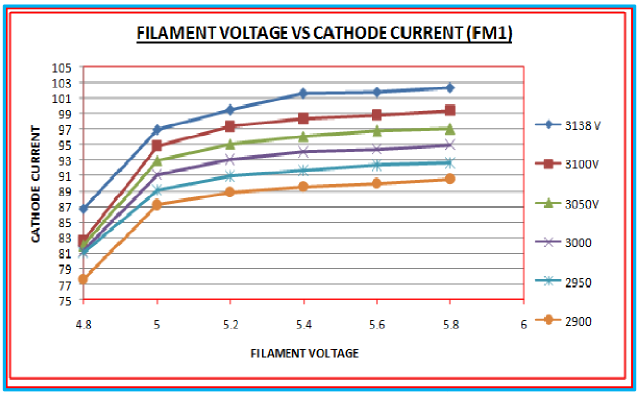


Table. RF Measurement with various cathode voltages

Cathode Voltage(V)	Po sat (W)	Test conditions
-3138	65	Filament Voltage = 5.4 V Frequency = 3.925 GHz All Collector voltages same as FM1
-3100	60	
-3050	56,5	
-3000	47	
-2950	40	
-2900	30	

FIG.2 Experiment results of Cathode voltage reduction

However measurement shows reduction in RF output power with reduction in cathode voltage as shown in the table.4 below. up to 3100 V the TWT is able to give the required 60W power. But below that it is reducing substantially.So a trade-off need to be done between the two operating points, one below knee point, i.e.VF=4.8V and one above knee point, i.e. VF=5.4V. The TWTA with filament voltage 4.8V (present operating point) and having less helix current (1.8mA) will be more efficient but output power variations are expected with filament voltage changes. If the TWT operate at a filament voltage of 5.4V , then it will be less efficient due to excess helix current (up to 7mA) but will be giving more stable output power in spite off variations in filament voltage. The tradeoff is made and the final operating point is as shown in the fig.3

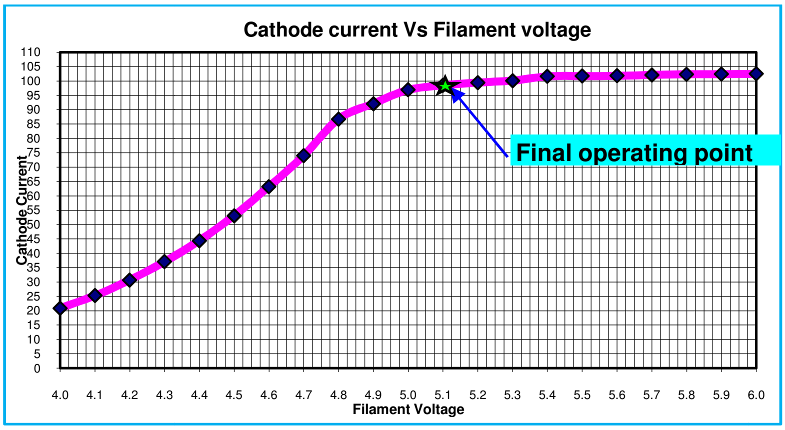


Fig.3 Final filament operating point recommended

Conclusion: It is recommended to use Vf=5.1V as the final operating point of filament with cathode voltage of 3138V and all other voltages remains unchanged from the present values for FM1 TWT. Also an RF characterization of the FM1 TWT with FM EPC is recommended at this operating point, before proceeding for potting of EPC, to ascertain the helix current and output power levels. The output power variations due to filament voltage variations shall be analyzed during the thermal cycling of integrated FM TWTA level acceptance test.

Acknowledgement: The authors are acknowledging the support from Director, SAC and TWT design team CEERI, EPC/TWT team from BEL, SAC, and various facilities at BEL for experiments.

REFERNCE

[1] G. Eason, B. Noble, and I.N. Sneddon, “On certain integrals of Lipschitz-Hankel type involving products of Bessel functions,” Phil. Trans. Roy.Soc.
London, vol. A247, pp. 529-551, April 1955. (*references*)
[2] J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68-73.
[3] I.S. Jacobs and C.P. Bean, “Fine particles, thin films and exchange anisotropy,” in Magnetism, vol. III, G.T. Rado and H. Suhl, Eds. New York: Academic,

