WS 12.2 ML-5681Triode

This Mathcad 14 worksheet is designed to accompany the author's book "Microwave and RF Vacuum Electronic Power Sources", Cambridge University Press (2018). The section, equation, and figure numbers refer to the corresponding sections, equations, and figures in the book. Data input fields are highlighted in yellow and output fields are highlighted in green.

This worksheet provides a model of the ML-5681 triode (see section 12.2.1)

The characteristics are computed using data from:

Rheaume, R. H. (1952). "A coaxial power triode for 50-kW output up to 110 Mc."
Proceedings of the IRE **40**(9): 1033-1037.

and

Machlett Laboratories Inc. (1962). ML-5681 Data Sheet.

The grid diameter, grid wire diameter and spacing were measured from the photo of the tube and scaled from the flange diameter. Note that the grid supports are well away from the filament wires and therefore the will have little effect on the screening factor.

Flange diameter $D_F := 8 \cdot in$

Grid length $L_g := \frac{168}{157} \cdot D_F$

Number of grid wires $N_g := 63$

Grid diameter $D_g := \frac{68}{157} \cdot D_F$

Grid wire separation $aa := \frac{L_g}{N_g}$

Anode length $L_a := 200 \cdot mm$

Shielding factor $S_g := \frac{1.1}{6.4}$

Grid wire radius $rr := S_g \cdot \frac{aa}{2}$

Approximate electrode spacings given in the paper

$d_e := 0.125 \cdot in$ $\quad d_2 := 3 \cdot d_e$

Summary of the tube dimensions

$D_g = 88.0 \cdot mm$ $\quad aa = 3.5 \cdot mm$ $\quad rr = 0.30 \cdot mm$ $\quad d_e = 3.175\,mm$ $\quad d_2 = 9.525\,mm$

Check anode internal diameter with external diameter (5.5") given in the data sheet

$D_a := D_g + 2 \cdot d_2$ $\quad D_a = 4.215 \cdot in$

This is sufficient for the thickness of the metal and of the water cooling chanels.

Tube dimensions used for modelling

$a := 3.5\cdot mm$ $\quad r := 0.3\cdot mm$ $\quad d_1 := d_e$ $\quad d_1 = 3.175\cdot mm$ $\quad d_2 = 9.525\cdot mm$

Check the penetration factor

$$D := -\frac{\ln\left(\tanh\left(\frac{2\pi\cdot r}{a}\right)\right)}{\frac{2\cdot\pi\cdot d_2}{a} - \ln\left(\cosh\left(\frac{2\pi\cdot r}{a}\right)\right)}$$

Equation 6.36

$$\mu := \frac{1}{D}$$

$D = 0.042$ $\quad \mu = 23.9$

The measurement of the screening factor from the photograph is not very accurate. It has been adjusted slightly so that the amplification factor is consistent with the figure in the paper (23), and in the data sheet (25). The characteristic curves show that mu is not quite constant but that in the centre of the range of operation it is about 27.

Calculate the normalised dimensions

$\frac{d_1}{a} = 0.907$ $\quad \frac{d_2}{a} = 2.721$ $\quad \frac{r}{a} = 0.086$

Inter-electrode capacitances

External capacitances for comparison

$$Ccg := \frac{a\cdot\varepsilon_0\cdot 16\cdot L_a}{d_1 + D\cdot(d_1 + d_2)}$$ $Ccg = 26.8\,pF$ $\quad C_{fg} := 76\cdot pF$

$$Cga := \frac{d_1}{d_2}\cdot Ccg$$ $Cga = 8.9\,pF$ $\quad C_{ga} := 61\cdot pF$

$$Cca := D\cdot Ccg$$ $Cca = 1.1\,pF$ $\quad C_{fa} := 2\cdot pF$

Filament dimensions

Tungsten filament with 16 legs comprising 8 pairs connected in parallel in series with the other 8. The resistance of the filament is thus 1/4 of that of a single wire. The length of the filament is determined from the photograph and the diameter of the filament wire from its resistance.

Filament length $L_f := \frac{152}{157} \cdot D_F$ $L_f = 197 \cdot mm$ $N_f := 16$ $R_f := 0.0062 \cdot \Omega$ $\rho := 5.4 \cdot 10^{-6} \cdot \Omega \cdot cm$

Filament diameter $D_f := D_g - 2 \cdot d_1$ $D_f = 81.7 \cdot mm$ This is very close to the value measured from the photograph.

Cross-sectional area and radius of filament wire

$$A_f := \frac{\rho \cdot (L_f + 0.5 \cdot D_f)}{R_f \cdot 4} \qquad r_f := \sqrt{\frac{A_f}{\pi}} \qquad r_f = 0.406 \cdot mm$$

The effective length of the filament is given as approximately 6 inches, that is 1/16 wavelength at 110 MHz

$$\lambda := \frac{c}{100 \cdot MHz} \qquad \frac{\lambda}{16} = 7.377 \cdot in$$

Choose $L_{ef} := 6.5 \cdot in$ $L_{ef} = 165 \cdot mm$

If r_f / d_e is small then the variation in electric field around the filament is negligible and the whole surface emits. Since the potential difference is fixed the field enhancement factor can be regarded as an adjustment to the effective spacing for the purpose of calculating the current. The effective surface area of the cathode is given in

Spangenberg, K. R. (1948). Vacuum Tubes, McGraw-Hill (p.191).

$$SA_f := N_f \cdot L_{ef} \cdot 2 \cdot d_1$$

Equation 12.16

$SA_f = 168\ cm^2$

Current-voltage characteristics

$$\eta := 1.759\cdot 10^{11}\cdot C\cdot kg^{-1}$$

$$KK := \frac{4}{9}\cdot\varepsilon_0\cdot\sqrt{2\cdot\eta}$$

$$I_c(V_g, V_a) := \begin{cases} \dfrac{KK\cdot SA_f\cdot\sqrt{1+D}\cdot(V_g + D\cdot V_a)^{1.5}}{[d_1 + D\cdot(d_1 + d_2)]^2} & \text{if } V_g + D\cdot V_a > 0 \wedge V_a \ge V_g \\ 0 & \text{otherwise} \end{cases}$$

Equation 6.56

With island formation

$$f1(y) := \frac{\sinh\left(\dfrac{2\cdot\pi\cdot d_1}{a}\right)}{\cosh\left(\dfrac{2\cdot\pi\cdot d_1}{a}\right) - \cos\left(\dfrac{2\cdot\pi\cdot y}{a}\right)}$$

Equation 6.39

$$D_E(y) := \frac{d_1\cdot(1 - f1(y)) + d_2\cdot D}{(d_1 + d_2)\cdot f1(y) - d_1}$$

Equation 6.45 using Equation 6.33

$$F_1(V_g, V_a, y) := \begin{cases} \dfrac{\sqrt{1 + D_E(y)}\cdot(V_g + D_E(y)\cdot V_a)^{1.5}}{[d_1 + D_E(y)\cdot(d_1 + d_2)]^2} & \text{if } V_g + D_E(y)\cdot V_a \ge 0 \\ 0 & \text{otherwise} \end{cases}$$

$$I_{c1}(V_g, V_a) := \frac{KK\cdot SA_f}{a}\cdot\int_0^a F_1(V_g, V_a, y)\,dy$$

Equation 6.67

Comparison of currents shows that island formation is not important in this tube.

$I_c(-300\cdot V, 10\cdot kV) = 3.74\,A$

$I_{c1}(-300\cdot V, 10\cdot kV) = 3.77\,A$

Grid current fraction

1. Grid current fraction given by Spangenberg p.230. Eq. (6.61)

$$\delta S := \frac{a}{\frac{a\cdot\mu}{\pi\cdot(\mu+1)}\cdot\frac{r}{2\cdot d_1}\cdot\ln\left(\frac{4e\cdot d_1}{r}\right)+2\cdot r} - 1$$

Equation 6.22

$$I_{gaS}(V_{ga}) := \frac{1}{\delta S}\cdot\sqrt{V_{ga}}$$

2. Jonker and Tellegen as cited in Beck p.321 (Eq. 6.66). V_{eg} is the effective grid potential

$$V_{eg\_g}(V_{ag}) := \frac{V_{ag}+\mu}{1+\mu+\frac{d_2}{d_1}}$$

$$V_{eg\_g} = \frac{V_{eg}}{V_g}$$

$$I_{ag}(V_{ag}) := \frac{a}{2\cdot r}\cdot\sqrt{V_{eg\_g}(V_{ag})}\cdot\left(\frac{2\cdot\ln\left(\frac{a}{2\cdot\pi\cdot r}\right)}{2\cdot\ln\left(\frac{a}{2\cdot\pi\cdot r}\right)+\frac{1}{V_{eg\_g}(V_{ag})}-1}\right)-1$$

$$I_{gaJ}(V_{ga}) := \frac{1}{I_{ag}\left(V_{ga}^{-1}\right)}$$

3. Empirical fit to the tube data

$$I_{gaE}(V_{ga}) := 0.67\sqrt{V_{ga}} - 0.2$$

4. Experimental grid current data table

ED :=

	0	1	2	3
	Anode Current (A)	Grid Current (A)	Anode Voltage (kV)	Grid Voltage (kV)
0	10	1	1.5	0.22
1	10	2	0.9	0.26
2	10	5	0.3	...

$$I_{gaD} := \frac{ED^{\langle 1\rangle}}{ED^{\langle 0\rangle}} \qquad V_{gaD} := \frac{ED^{\langle 3\rangle}}{ED^{\langle 2\rangle}}$$

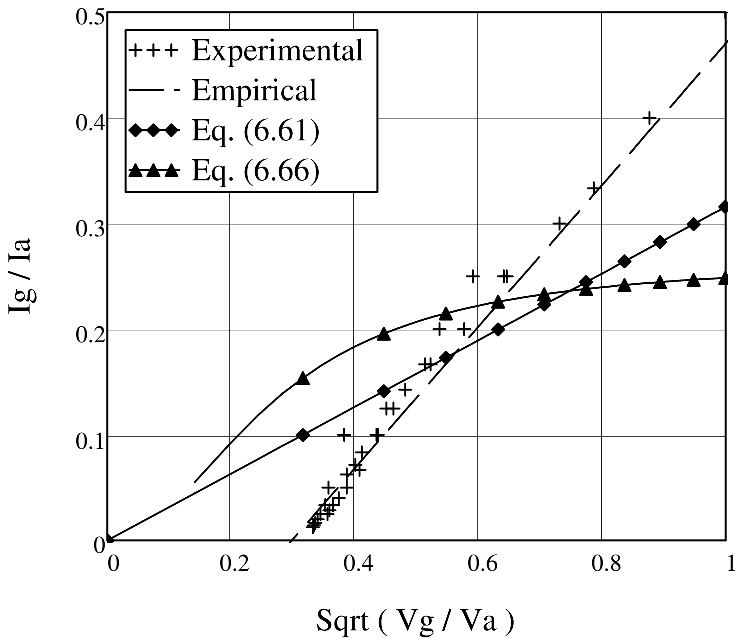


Figure 12.8

Grid and Anode currents calculated using the emprical grid current model (3).

$$I_g(V_g, V_a) := \begin{cases} \dfrac{I_c(V_g, V_a)}{1 + \left(I_{gaE}\left(\left|\dfrac{V_g}{V_a}\right|\right)\right)^{-1}} & \text{if } I_{gaE}\left(\left|\dfrac{V_g}{V_a}\right|\right) > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$I_a(V_g, V_a) := I_c(V_g, V_a) - I_g(V_g, V_a)$$

Anode currents $Ia := (80\ \ 70\ \ 60\ \ 50\ \ 40\ \ 30\ \ 20\ \ 10\ \ 5\ \ 1)^T \cdot A$

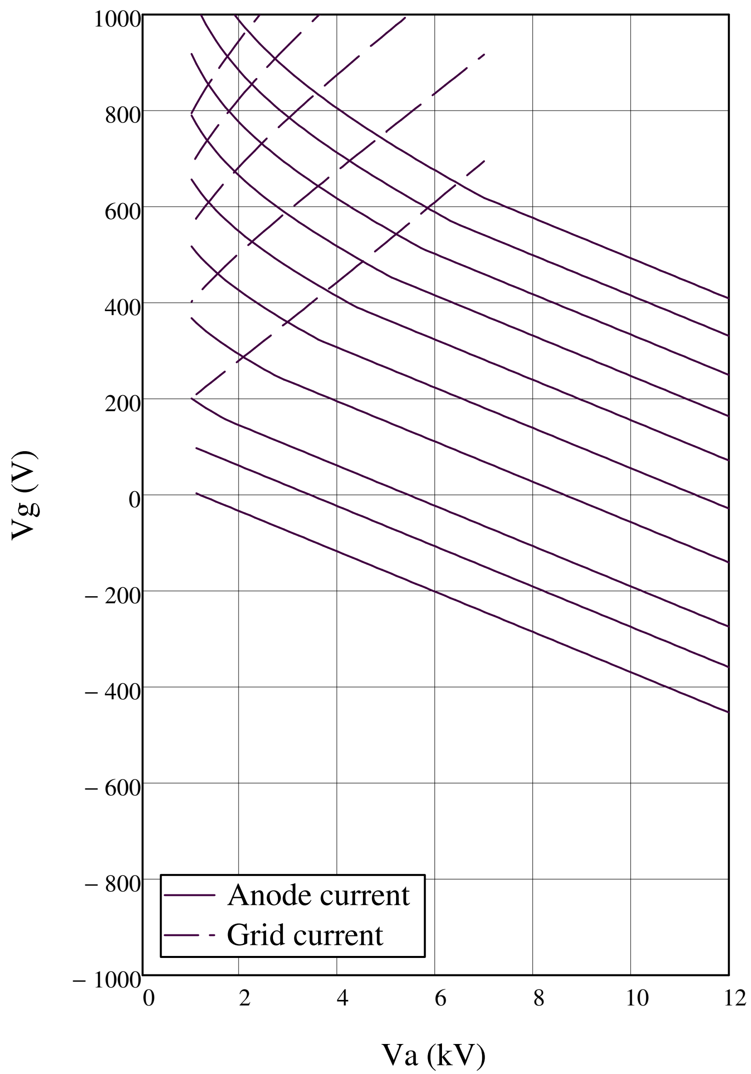
Grid currents $Ig := (20\ \ 15\ \ 10\ \ 5\ \ 1)^T \cdot A$

$V_g := 1000 \cdot V$

$Vg(Ia, V_a) := \mathrm{root}(I_a(V_g, V_a) - Ia, V_g)$ Curves of constant anode current

$Vg2(Ig, V_a) := \mathrm{root}(I_g(V_g, V_a) - Ig, V_g)$ Curves of constant grid current

Plotting ranges $V_a := 0, 0.1 \cdot kV .. 12 \cdot kV$ $V_{a2} := 0, 0.1 \cdot kV .. 7 \cdot kV$ $n := 0 .. 9$ $nn := 0 .. 4$



$$Ig = \begin{pmatrix} 20 \\ 15 \\ 10 \\ 5 \\ 1 \end{pmatrix} A$$

$$Ia = \begin{pmatrix} 80 \\ 70 \\ 60 \\ 50 \\ 40 \\ 30 \\ 20 \\ 10 \\ 5 \\ 1 \end{pmatrix} A$$

Figure 12.9

Compare figure 12.7

Cathode-grid transit time calculations

For class B operation with Va = 1.5 kV (min)

$V_{g1} := 515 \cdot V$ $V_{amin} := 1500 \cdot V$ $f := 110 \cdot MHz$

Effective grid voltage at maximum current $V_{eg} := V_{eg\_g}\left(\frac{V_{amin}}{V_{g1}}\right) \cdot V_g$ $V_{eg} = 961\ V$

Electron velocity $u_g := \sqrt{2 \cdot \eta \cdot V_{eg}}$

Normalised transit time $\tau := \frac{3d_1}{u_g} \cdot f = 0.057$ Equation 5.20 $\tau = 0.057$

$\beta_e := \frac{2 \cdot \pi \cdot f}{u_g}$

Current increased by approximately $\sqrt{1 + \left(2\beta_e \cdot d_1\right)^2} = 1.028$ Following equation 5.95