

Field Cage design

For flashover, we are operating on the right side of the Paschen curve; increasing pressure gives increasing resistance to flashover. Therefore, we need to make sure flashover does not occur at lowest operating pressure and internal breakdown does not occur at highest operating pressure.

PCB substrate thickness:

For PTFE, we need to use a thick substrate for rigidity, best estimate is 1.5mm. Dielectric strength for this thickness is typically:

$$E_{bd_PTFE_thk} := 285 \frac{kV}{in} \quad \text{from: } \text{http://www.boedeker.com/teflon_p.htm} \text{ (lowest number found, for thinner substrates 500 V/mil is typ.)}$$

To give rigidity in the longitudinal direction, we use overlapping traces on both sides and limit the trace to trace width, so as to minimize the longitudinal breaks in the sandwich structure.

IPC typ. V_{bd} is 30-40 V/mil @ 1 atm air

Xenon relative (to air) electric strength

$$E_{tr} := 30 \frac{kV}{in} \quad E_{tr} = 1.181 \frac{kV}{mm}$$

$$\eta_{Xe} := 0.8$$

DRAFT

lowest pressure used:

$$P_{Xe_l} := 150 \text{ psi}$$

highest pressure used

$$P_{Xe_h} := 300 \text{ psi}$$

Maximum allowable trace to trace voltage gradient

Pressure multiplier for gas breakdown:

$$\beta_{pXe} := \eta_{Xe} \cdot \frac{P_{Xe_l}}{15 \text{ psi}} \quad \beta_{pXe} = 8$$

Gas Dielectric Strength

$$E_{tr_TPC} := \beta_{pXe} \cdot E_{tr} \quad E_{tr_TPC} = 9 \frac{kV}{mm} \quad E_{tr_TPC} = 240 \frac{kV}{in}$$

Gas breakdown is limit at lower pressure, but just barely.

Highest field cage gradient is end region(s) with:

$$V_{end} := 20 \text{ kV}$$

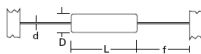
We need a minimum total gap width of:

$$w_{gap} := \frac{V_{end}}{E_{tr_TPC}} \quad w_{gap} = 2.117 \text{ mm} \quad \text{to avoid flashover. Over 10 gaps, we could have a trace to trace gap of 0.25mm, but this could be difficult to fab well. We double trace gap to } \sim 0.5 \text{ mm}$$

		GC55	GC65	GC70
Power rating at 70°C	watts	0.25	0.5	1.0
Resistance range	ohms	47k to 900 meg	47k to 900 meg	47k to 1G
Limiting element voltage	Volts dc or ac Peak	1700	3500	10000
Isolation voltage	volts		700	
TCR (20°C to 70°C)	ppm/°C		100	
Resistance tolerance	%		1, 2, 5	
Values		E24 & E96 preferred		
Thermal impedance	°C/watt	140	90	70
Ambient temperature range	°C	- 55 to 155		

Physical Data

Dimensions (mm) and Weight (g)							
Type	L max.	D max.	f min.	d nom.	PCB mounting centres	Min bend radius	Wt nom.
GC55	6.2	2.5	21.0	0.6	10.2	0.6	0.3
GC65	9.0	3.6	19.6	0.8	13.7	1.2	0.6
GC70	14.5	5.3	23.6	0.8	20.3	1.2	1.1



Single layer design on 1/4 " PTFE

trace to race centerline distance (pitch)

gap width

$$p_{sl} := 6\text{mm}$$

$$w_{gsl} := 1\text{mm}$$

trace width

$$w_{tr} := p_{sl} - w_{gsl} \quad w_{tr} = 5\text{ mm}$$

Trace voltages and resistor values

Voltage on traces will be set proportionally to their centerline positions. This method does not correct for the harmonics introduced by the asymmetric mesh frames, but until they are determined to be significant, this will remain the baseline design. We start from the PMT mesh plane and work through the three field cage regions, called here the cathode, drift and anode field cages. There is no field cage in the electroluminescent region (EL) where voltage jumps from +11 kV to = 20 kV across a 3mm gap.

Nominal Intertrace Resistance (may or may not be the same for all regions)

$$R_{it} := 100\text{M}\Omega$$

Cathode (PMT to drift start; -1 kV to -20kV)

Mesh voltages

Mesh positions along axis

$$V_{cl} := -1\text{kV} \quad V_{ch} := -20\text{kV} \quad z_{cl} := 0\text{cm (baseline)} \quad z_{ch} := 5\text{cm}$$

First trace (centerline) position

$$z_{c0} := 1.0645\text{cm}$$

There are 7 traces, and thus 8 resistors (2 end resistors and 6 intertrace resistors):

$$n_{tc} := 7$$

trace number:

$$i_c := 1, 2 \dots n_{tc}$$

trace centerline position:

$$z_c(i_c) := z_{c0} + p_{sl} \cdot (i_c - 1)$$

$$z_c(i_c) = \begin{pmatrix} 1.065 \\ 1.664 \\ 2.264 \\ 2.865 \\ 3.465 \\ 4.064 \\ 4.665 \end{pmatrix} \text{cm}$$

trace voltages

$$V_c(i_c) := \frac{V_{ch} - V_{cl}}{z_{ch} - z_{cl}} \cdot z_c(i_c) + V_{cl}$$

$$V_c(i_c) = \begin{pmatrix} -5.045 \\ -7.325 \\ -9.605 \\ -11.885 \\ -14.165 \\ -16.445 \\ -18.725 \end{pmatrix} \text{kV}$$

Max power, per panel

$$P_{max} := 1\text{W}$$

Min resistance total:

$$R_{tc} := \frac{(V_{ch} - V_{cl})^2}{P_{max}} \quad R_{tc} = 361\text{ M}\Omega$$

Number of resistors (assume all same for start)

$$N_{rc} := n_{tc} + 1$$

Intertrace resistance, minimum:

$$R_{c_min} := \frac{R_{tc}}{N_{rc}} \quad R_{c_min} = 45.125\text{ M}\Omega$$

Choose intertrace resistor value:

$$R_c := R_{it} \quad R_c = 100\text{ M}\Omega$$

End resistor values:

$$R_{cl} := R_c \cdot \frac{z_{c0}}{p_{sl}} \quad R_{cl} = 177.417 \text{ M}\Omega \quad \text{low side, } z_c = 0 \text{ cm}$$

$$R_{ch} := R_c \cdot \frac{(z_{ch} - z_c(n_{tc}))}{p_{sl}} \quad R_{ch} = 55.9 \text{ M}\Omega \quad \text{high side } z_c = 5 \text{ cm}$$

Resistance total:

$$R_{ct} := R_{cl} + (n_{tc} - 1) \cdot R_c + R_{ch} \quad R_{ct} = 833.3 \text{ M}\Omega$$

trace voltages, actual, are now:

$$V_{c_a}(i_c) := (V_{ch} - V_{cl}) \cdot \frac{[R_{cl} + R_c \cdot (i_c - 1)]}{R_{ct}} + V_{cl}$$

$$\Delta V_c := V_c(1) - V_c(2) \quad \Delta V_c = 2.28 \text{ kV} \quad V_{c_a}(i_c) = \begin{pmatrix} -5.045 \\ -7.325 \\ -9.605 \\ -11.885 \\ -14.165 \\ -16.445 \\ -18.725 \end{pmatrix} \text{ kV} \quad \text{compare -->} \quad V_c(i_c) = \begin{pmatrix} -5.045 \\ -7.325 \\ -9.605 \\ -11.885 \\ -14.165 \\ -16.445 \\ -18.725 \end{pmatrix} \text{ kV}$$

$$\Delta V_{cl} := V_{cl} - V_c(1) \quad \Delta V_{cl} = 4.045 \text{ kV} \quad \text{<--use 2 resistors for R low}$$

$$\Delta V_{ch} := V_c(n_{tc}) - V_{ch} \quad \Delta V_{ch} = 1.275 \text{ kV}$$

We will need to use a network of resistors on each end to obtain the proper resistance values. These resistors will be mounted to the support panel.

$$\text{Current: } I_c := \frac{V_{ch} - V_{cl}}{R_{ct}} \quad I_c = -0.023 \text{ mA}$$

$$\text{Power: } P_c := \frac{(V_{ch} - V_{cl})^2}{R_{ct}} \quad P_c = 0.433 \text{ W}$$

Power per resistor

intertrace	low	high
$P_{rc} := I_c^2 R_c$	$P_{rcl} := I_c^2 R_{cl}$	$P_{rch} := I_c^2 R_{ch}$
$P_{rc} = 0.052 \text{ W}$	$P_{rcl} = 0.092 \text{ W}$	$P_{rch} = 0.029 \text{ W}$

Trace to trace gap:

$$z_{tt} := .07 \text{ cm}$$

Trace to trace voltage gradient

$$E_c := \frac{V_c(1) - V_c(2)}{z_{tt}} \quad E_c = 32.571 \frac{\text{kV}}{\text{cm}} \quad E_c = 82.7 \frac{\text{kV}}{\text{in}}$$

Mesh frame to trace distances:

$$g_{cl} := 0.2 \text{ cm} \quad g_{ch} := .085 \text{ cm}$$

Mesh frame to trace voltage gradients

$$E_{cl} := \frac{V_{cl} - V_c(1)}{g_{cl}} \quad E_{cl} = 20.2 \frac{\text{kV}}{\text{cm}}$$

$$E_{ch} := \frac{V_c(n_{tc}) - V_{ch}}{g_{ch}} \quad E_{ch} = 15 \frac{\text{kV}}{\text{cm}}$$

All gap gradients are lower than the standard design value multiplied by the pressure/gas ratio as calculated above:

$$E_{tr_TPC} = 94.5 \frac{\text{kV}}{\text{cm}}$$

Drift (drift start to EL start; -20 kV to +11kV))

Mesh voltages

Mesh positions along axis

$$V_{dl} := -20\text{kV} \quad V_{dh} := 11\text{kV} \quad z_{dl} := 0\text{cm (baseline)} \quad z_{dh} := 8\text{cm}$$

First trace position

$$z_{d0} := 1.0\text{cm}$$

There are 11 traces, and thus 12 resistors (2 end resistors and 10 intertrace resistors):

$$n_{td} := 11$$

trace number:

$$i_d := 1, 2.. n_{td}$$

trace centerline position:

$$z_d(i_d) := z_{d0} + p_{sl} \cdot (i_d - 1)$$

$$z_d(i_d) = \begin{pmatrix} 1 \\ 1.6 \\ 2.2 \\ 2.8 \\ 3.4 \\ 4 \\ 4.6 \\ 5.2 \\ 5.8 \\ 6.4 \\ 7 \end{pmatrix} \text{ cm}$$

trace voltages

$$V_d(i_d) := \frac{V_{dh} - V_{dl}}{z_{dh} - z_{dl}} \cdot z_d(i_d) + V_{dl}$$

$$V_d(i_d) = \begin{pmatrix} -16.125 \\ -13.8 \\ -11.475 \\ -9.15 \\ -6.825 \\ -4.5 \\ -2.175 \\ 0.15 \\ 2.475 \\ 4.8 \\ 7.125 \end{pmatrix} \text{ kV}$$

Max power, per panel

$$P_{\max} = 1 \text{ W}$$

Min resistance total:

$$R_{td} := \frac{(V_{dh} - V_{dl})^2}{P_{\max}} \quad R_{td} = 961 \text{ M}\Omega$$

Number of resistors (assume all same for start)

$$N_{rd} := n_{td} + 1$$

Intertrace resistance, minimum:

$$R_{d_min} := \frac{R_{td}}{N_{rd}} \quad R_{d_min} = 80.083 \text{ M}\Omega$$

Choose intertrace resistor value:

$$R_d := R_{it} \quad R_d = 100 \text{ M}\Omega$$

End resistor values:

$$R_{dl} := R_d \cdot \frac{z_{d0}}{p_{sl}} \quad R_{dl} = 166.7 \text{ M}\Omega \quad \text{low side } z_d=0$$

$$R_{dh} := R_d \cdot \frac{(z_{dh} - z_d(n_{td}))}{p_{sl}} \quad R_{dh} = 166.67 \text{ M}\Omega \quad \text{high side } z_d=8\text{cm}$$

Resistance total :

$$R_{dt} := R_{dl} + (n_{td} - 1)R_d + R_{dh}$$

$$R_{dt} = 1.333 \text{ G}\Omega$$

Trace voltages, actual, are now:

$$V_{da}(i_d) := (V_{dh} - V_{dl}) \cdot \frac{[R_{dl} + R_d \cdot (i_d - 1)]}{R_{dt}} + V_c \quad V_{da}(i_d) = \begin{pmatrix} -16.125 \\ -13.8 \\ -11.475 \\ -9.15 \\ -6.825 \\ -4.5 \\ -2.175 \\ 0.15 \\ 2.475 \\ 4.8 \\ 7.125 \end{pmatrix} \text{ kV} \quad \text{compare -->} \quad V_d(i_d) = \begin{pmatrix} -16.125 \\ -13.8 \\ -11.475 \\ -9.15 \\ -6.825 \\ -4.5 \\ -2.175 \\ 0.15 \\ 2.475 \\ 4.8 \\ 7.125 \end{pmatrix} \text{ kV}$$

$$\Delta V_d := V_d(2) - V_d(1) \quad \Delta V_d = 2.325 \text{ kV}$$

$$\Delta V_{dl} := V_d(1) - V_{dl} \quad \Delta V_{dl} = 3.875 \text{ kV} \quad \text{<-use 2 resistors for } R_l$$

$$\Delta V_{dh} := V_{dh} - V_d(n_{td}) \quad \Delta V_{dh} = 3.875 \text{ kV} \quad \text{<-use 2 resistors for } R_h$$

We will need to use a network of resistors on each end to obtain the proper resistance values. These resistors will be mounted to the support panel.

$$\text{Current: } I_d := \frac{V_{dh} - V_{dl}}{R_{dt}} \quad I_c = -0.023 \text{ mA}$$

$$\text{Power: } P_d := \frac{(V_{dh} - V_{dl})^2}{R_{dt}} \quad P_d = 0.721 \text{ W}$$

Power per resistor

intertrace	low	high
$P_{rd} := I_d^2 R_d$	$P_{rdl} := I_d^2 R_{dl}$	$P_{rdh} := I_d^2 R_{dh}$
$P_{rd} = 0.054 \text{ W}$	$P_{rdl} = 0.09 \text{ W}$	$P_{rdh} = 0.09 \text{ W}$

Trace to trace gap:

$$z_{tt} = 0.07 \text{ cm}$$

Trace to trace voltage gradient

$$E_d := \frac{V_d(2) - V_d(1)}{z_{tt}} \quad E_d = 33.214 \frac{\text{kV}}{\text{cm}} \quad E_d = 84.4 \frac{\text{kV}}{\text{in}}$$

Mesh frame to trace distances:

$$g_{dl} := 0.2 \text{ cm} \quad g_{dh} := 0.2 \text{ cm}$$

Mesh frame to trace voltage gradients

$$E_{dl} := \frac{V_d(1) - V_{dl}}{\xi_{dl}} \quad E_{dl} = 19.4 \frac{\text{kV}}{\text{cm}}$$

$$E_{dh} := \frac{V_{dh} - V_d(n_{td})}{\xi_{dh}} \quad E_{dh} = 19.4 \frac{\text{kV}}{\text{cm}}$$

All gap gradients are lower than the standard design value multiplied by the pressure/gas ratio as calculated above:

Anode (EL end to SiPMT plane; +20 kV to 0kV)

Mesh voltages

Mesh positions along axis

$$V_{al} := 20\text{kV} \quad V_{ah} := 0\text{kV}$$

$$z_{al} := 0\text{cm (baseline)}$$

$$z_{ah} := 5\text{cm}$$

First trace centerline position

$$z_{a0} := 1.0\text{cm}$$

There are 6 traces, and thus 7 resistors (2 end resistors and 5 intertrace resistors):

$$n_{ta} := 6$$

trace number:

$$i_a := 1, 2 \dots n_{ta}$$

trace centerline position:

$$z_a(i_a) := z_{a0} + p_{sl} \cdot (i_a - 1)$$

$$z_a(i_a) = \begin{pmatrix} 1 \\ 1.6 \\ 2.2 \\ 2.8 \\ 3.4 \\ 4 \end{pmatrix} \text{cm}$$

trace voltages

$$V_a(i_a) := \frac{V_{ah} - V_{al}}{z_{ah} - z_{al}} \cdot z_a(i_a) + V_{al}$$

$$V_a(i_a) = \begin{pmatrix} 16 \\ 13.6 \\ 11.2 \\ 8.8 \\ 6.4 \\ 4 \end{pmatrix} \text{kV}$$

Max power, per panel

$$P_{\max} = 1 \text{ W}$$

Min resistance total:

$$R_{ta} := \frac{(V_{ah} - V_{al})^2}{P_{\max}} \quad R_{ta} = 400 \text{ M}\Omega$$

Number of resistors (assume all same for start)

$$N_{ra} := n_{ta} + 1$$

Intertrace resistance, minimum:

$$R_{a_min} := \frac{R_{ta}}{N_{ra}} \quad R_{a_min} = 57.143 \text{ M}\Omega$$

Choose intertrace resistor value:

$$R_a := R_{it} \quad R_a = 100 \text{ M}\Omega$$

End resistor values:

$$R_{al} := R_a \cdot \frac{z_{a0}}{p_{sl}} \quad R_{al} = 166.7 \text{ M}\Omega \quad \text{low side, } z_a = 0 \text{ cm}$$

$$R_{ah} := R_a \cdot \frac{(z_{ah} - z_a(n_{ta}))}{p_{sl}} \quad R_{ah} = 166.7 \text{ M}\Omega \quad \text{high side } z_a = 5 \text{ cm}$$

Resistance total:

$$R_{at} := R_{al} + (n_{ta} - 1) \cdot R_a + R_{ah} \quad R_{at} = 833.3 \text{ M}\Omega$$

trace voltages, actual, are now:

$$V_{a_a}(i_a) := (V_{ah} - V_{al}) \cdot \frac{[R_{al} + R_a \cdot (i_a - 1)]}{R_{at}} + V_{al}$$

$$V_{a_a}(i_a) = \begin{pmatrix} 16 \\ 13.6 \\ 11.2 \\ 8.8 \\ 6.4 \\ 4 \end{pmatrix} \text{ kV} \quad \text{compare -->} \quad V_a(i_a) = \begin{pmatrix} 16 \\ 13.6 \\ 11.2 \\ 8.8 \\ 6.4 \\ 4 \end{pmatrix} \text{ kV}$$

$$\Delta V_a := V_a(1) - V_a(2) \quad \Delta V_a = 2.4 \text{ kV}$$

$$\Delta V_{al} := V_{al} - V_a(1) \quad \Delta V_{al} = 4 \text{ kV} \quad \text{<-use 2 resistors for } R_l$$

$$\Delta V_{ah} := V_a(n_{ta}) - V_{ah} \quad \Delta V_{ah} = 4 \text{ kV} \quad \text{<-use 2 resistors for } R_h$$

We will need to use a network of resistors on each end to obtain the proper resistance values. These resistors will be mounted to the support panel.

$$\text{Current: } I_a := \frac{V_{ah} - V_{al}}{R_{at}} \quad I_a = -0.024 \text{ mA}$$

$$\text{Power: } P_a := \frac{(V_{ah} - V_{al})^2}{R_{at}} \quad P_a = 0.48 \text{ W}$$

Power per resistor

intertrace low high

$$P_{ra} := I_a^2 R_a \quad P_{ral} := I_a^2 R_{al} \quad P_{rah} := I_a^2 R_{ah}$$

$$P_{ra} = 0.058 \text{ W} \quad P_{ral} = 0.096 \text{ W} \quad P_{rah} = 0.096 \text{ W}$$

Trace to trace gap:

$$z_{tt} = 0.07 \text{ cm}$$

Trace to trace voltage gradient

$$E_a := \frac{V_a(1) - V_a(2)}{z_{tt}} \quad E_a = 34.286 \frac{\text{kV}}{\text{cm}} \quad E_a = 87.1 \frac{\text{kV}}{\text{in}}$$

Mesh frame to trace distances:

$$g_{al} := 0.22 \text{ cm} \quad g_{ah} := 0.22 \text{ cm}$$

Mesh frame to trace voltage gradients

$$E_{al} := \frac{V_{al} - V_a(1)}{g_{al}} \quad E_{al} = 18.2 \frac{\text{kV}}{\text{cm}}$$

$$E_{ah} := \frac{V_a(n_{ta}) - V_{ah}}{g_{ah}} \quad E_{ah} = 18.2 \frac{\text{kV}}{\text{cm}}$$

All gap gradients are lower than the standard design value multiplied by the pressure/gas ratio as calculated above:

$$E_{tr_TPC} = 94.5 \frac{\text{kV}}{\text{cm}}$$

<u>Summary</u>	cathode	drift	anode
Trace to trace voltages:			
	$\Delta V_c = 2.28 \text{ kV}$	$\Delta V_d = 2.325 \text{ kV}$	$\Delta V_a = 2.4 \text{ kV}$
Intertrace resistance			
	$R_c = 100 \text{ M}\Omega$	$R_d = 100 \text{ M}\Omega$	$R_a = 100 \text{ M}\Omega$
Intertrace resistor power			
	$P_{rc} = 0.052 \text{ W}$	$P_{rd} = 0.054 \text{ W}$	$P_{ra} = 0.058 \text{ W}$

End Voltages

$$\Delta V_{cl} = 4045 \text{ V} \quad \Delta V_{ch} = 1275 \text{ V} \quad \Delta V_{dl} = 3875 \text{ V} \quad \Delta V_{dh} = 3875 \text{ V} \quad \Delta V_{al} = 4000 \text{ V} \quad \Delta V_{ah} = 4000 \text{ V}$$

End resistances

$$R_{cl} = 177.4 \text{ M}\Omega \quad R_{ch} = 55.9 \text{ M}\Omega \quad R_{dl} = 166.7 \text{ M}\Omega \quad R_{dh} = 166.7 \text{ M}\Omega \quad R_{al} = 166.7 \text{ M}\Omega \quad R_{ah} = 166.7 \text{ M}\Omega$$

End resistor voltage ratings

$$V_{cerl} := 1.5 \text{ kV} \quad V_{cerh_50} := 1.5 \text{ kV} \quad V_{da_er_100} := 2.5 \text{ kV} \quad V_{da_er_50} := 1.5 \text{ kV} \quad V_{da_er_15} := 1.5 \text{ kV} \\ V_{cerh_6} := 250 \text{ V}$$

use (180||180)+(180||180) use 50+6 |-----use 100+50+15)-----

Resistance totals, per panel

$$R_{ct} = 0.833 \text{ G}\Omega \quad R_{dt} = 1.333 \text{ G}\Omega \quad R_{at} = 0.833 \text{ G}\Omega$$

Power, per panel

$$P_c = 0.433 \text{ W} \quad P_d = 0.721 \text{ W} \quad P_a = 0.48 \text{ W}$$

Resistance totals, per chain (panel set)

$$R_{ctc} := \frac{R_{ct}}{6} \quad R_{ctc} = 138.9 \text{ M}\Omega \quad R_{dte} := \frac{R_{dt}}{6} \quad R_{dte} = 222.2 \text{ M}\Omega \quad R_{ate} := \frac{R_{at}}{6} \quad R_{ate} = 138.9 \text{ M}\Omega$$

Power, per chain (panel set)

$$P_{ctc} := 6P_c \quad P_{ctc} = 2.6 \text{ W} \quad P_{dte} := 6P_d \quad P_{dte} = 4.32 \text{ W} \quad P_{ate} := 6P_a \quad P_{ate} = 2.88 \text{ W}$$

Total power:

$$P_t := P_{ctc} + P_{dte} + P_{ate} \quad P_t = 9.8 \text{ W}$$

Total Number of intertrace resistors:

$$N_{it} := 6 \cdot (n_{tc} + n_{td} + n_{ta} - 3) \quad N_{it} = 126$$