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:

$$E_{bd\_PTFE\_thk} := 285\,\frac{kV}{in}$$

from: http://www.boedeker.com/teflon_p.htm (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 too minimize the longitudinal breaks in the sandwich structure.

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

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

Xenon relative (to air) electric strength

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

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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:

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

Gas Dielectric Strength

$$E_{tr\_TPC} := \beta_{pXe}\cdot E_{tr} \qquad E_{tr\_TPC} = 9\,\frac{kV}{mm} \qquad E_{tr\_TPC} = 240\,\frac{kV}{in}$$

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:

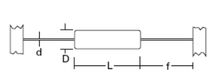
$$w_{gap} := \frac{V_{end}}{E_{tr\_TPC}} \qquad w_{gap} = 2.117\,\text{mm}$$

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 ~0.5mm

		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

using 6.7mm max resistor length :

max l   gap width   trace overhang

$l_r := 6.7\text{mm}$ $w_{gsl} := .7\text{mm}$ $w_e := .1\text{mm}$ additional end clearance

$2p_{sl} := \left(0.5w_{gsl} + w_e + l_r + w_e + 0.5w_{gsl}\right)$ <--counting length across 2 pitches

$p_{sl} := 0.5\left(l_r + 2w_e + w_{gsl}\right)$ $p_{sl} = 3.8\,\text{mm}$

$2w_{tr} := 2p_{sl} - \left(0.5w_{gsl} + w_{gsl} + 0.5w_{gsl}\right)$

$w_{tr} := p_{sl} - w_{gsl}$ $w_{tr} = 3.1\,\text{mm}$

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.

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

Mesh voltages   Mesh positions along axis

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

First trace (centerline) position

$z_{c0} := .9595\text{cm}$

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

trace number:

$i_c := 1, 2 .. 11$

trace centerline position:

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

$$z_c(i_c) = \begin{pmatrix} 0.96 \\ 1.34 \\ 1.72 \\ 2.099 \\ 2.48 \\ 2.86 \\ 3.24 \\ 3.619 \\ 4 \\ 4.38 \\ 4.76 \end{pmatrix}\text{cm}$$

trace voltages

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

$$V_c(i_c) = \begin{pmatrix} -4.646 \\ -6.09 \\ -7.534 \\ -8.978 \\ -10.422 \\ -11.866 \\ -13.31 \\ -14.754 \\ -16.198 \\ -17.642 \\ -19.086 \end{pmatrix}\text{kV}$$

Max power, per panel

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

Min resistance total:

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

Number of resistors (assume all same for start)

$N_{rc} := 12$

Intertrace resistance, minimum:

$$R_{c\_min} := \frac{R_{tc}}{N_{rc}} \qquad R_{c\_min} = 30.083\,M\Omega$$

Choose intertrace resistor value:

$$R_c := 50M\Omega$$

End resistor values:

$$R_{cl} := R_c \cdot \frac{z_{c0}}{p_{sl}} \qquad R_{cl} = 126.25\,M\Omega$$ low side, z_c= 0 cm

$$R_{ch} := R_c \cdot \frac{(z_{ch} - z_c(11))}{p_{sl}} \qquad R_{ch} = 31.6\,M\Omega$$ high side z_c = 5 cm

total initial resistance:

$$R_{ct} := R_{cl} + 10 \cdot R_c + R_{ch} \qquad R_{ct} = 657.9\,M\Omega$$

trace voltages, actual, are now:

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

$$V_{c\_a}(i_c) = \begin{pmatrix} -4.646 \\ -6.09 \\ -7.534 \\ -8.978 \\ -10.422 \\ -11.866 \\ -13.31 \\ -14.754 \\ -16.198 \\ -17.642 \\ -19.086 \end{pmatrix} kV$$

compare -->

$$V_c(i_c) = \begin{pmatrix} -4.646 \\ -6.09 \\ -7.534 \\ -8.978 \\ -10.422 \\ -11.866 \\ -13.31 \\ -14.754 \\ -16.198 \\ -17.642 \\ -19.086 \end{pmatrix} kV$$

$$\Delta V_c := V_c(1) - V_c(2) \qquad \Delta V_c = 1.444\,kV$$

$$\Delta V_{cl} := V_{cl} - V_c(1) \qquad \Delta V_{cl} = 3.646\,kV$$

$$\Delta V_{ch} := V_c(11) - V_{ch} \qquad \Delta V_{ch} = 0.914\,kV$$

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.

Current: $I_c := \frac{V_{ch} - V_{cl}}{R_{ct}} \qquad I_c = -0.029\,mA$

Power: $P_c := \frac{(V_{ch} - V_{cl})^2}{R_{ct}} \qquad P_c = 0.549\,W$

Power per resistor

intertrace	low	high
$P_{rc} := I_c^{\,2} R_c$	$P_{rcl} := I_c^{\,2} R_{cl}$	$P_{rch} := I_c^{\,2} R_{ch}$
$P_{rc} = 0.042\,W$	$P_{rcl} = 0.105\,W$	$P_{rch} = 0.026\,W$

Trace to trace gap:

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

Trace to trace voltage gradient

$$E_c := \frac{V_c(1) - V_c(2)}{z_{tt}} \qquad E_c = 20.629\,\frac{kV}{cm} \qquad E_c = 52.4\,\frac{kV}{in}$$

Mesh frame to trace distances:

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

Mesh frame to trace voltage gradients

$$E_{cl} := \frac{V_{cl} - V_c(1)}{g_{cl}} \qquad E_{cl} = 18.2\,\frac{kV}{cm}$$

$$E_{ch} := \frac{V_c(11) - V_{ch}}{g_{ch}} \qquad E_{ch} = 10.8\,\frac{kV}{cm}$$

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

$$E_{tr\_TPC} = 94.5\,\frac{kV}{cm}$$

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

Mesh voltages

$V_{dl} := -20kV \quad V_{dh} := 11kV$

Mesh positions along axis

$z_{dl} := 0cm$ (baseline) $\qquad z_{dh} := 8cm$

First trace position

$z_{d0} := .956cm$

There are 17 traces, and thus 18 resistors (2 end resistors and 16 intertrace resistors):

trace number:

$i_d := 1, 2 .. 17$

trace centerline position:

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

$$z_d(i_d) = \begin{pmatrix} 0.956 \\ 1.336 \\ 1.716 \\ 2.096 \\ 2.476 \\ 2.856 \\ 3.236 \\ 3.616 \\ 3.996 \\ 4.376 \\ 4.756 \\ 5.136 \\ 5.516 \\ 5.896 \\ 6.276 \\ 6.656 \\ 7.036 \end{pmatrix} cm$$

trace voltages

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

$$V_d(i_d) = \begin{pmatrix} -16.296 \\ -14.823 \\ -13.351 \\ -11.878 \\ -10.406 \\ -8.933 \\ -7.46 \\ -5.988 \\ -4.516 \\ -3.043 \\ -1.571 \\ -0.098 \\ 1.375 \\ 2.847 \\ 4.319 \\ 5.792 \\ 7.265 \end{pmatrix} kV$$

Max power, per panel

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

Min resistance total:

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

Number of resistors (assume all same for start)

$$N_{rd} := 18$$

Intertrace resistance, minimum:

$$R_{d\_min} := \frac{R_{tc}}{N_{rd}} \qquad R_{d\_min} = 20.056\,M\Omega$$

Choose intertrace resistor value:

$$R_d := 50M\Omega$$

End resistor values:

$$R_{dl} := R_d \cdot \frac{z_{d0}}{p_{sl}} \qquad R_{dl} = 125.8\,M\Omega$$ low side z_d=0

$$R_{dh} := R_d \cdot \frac{(z_{dh} - z_d(17))}{p_{sl}} \qquad R_{dh} = 126.84\,M\Omega$$ high sid z_d=8cm

Resistance total :

$$R_{dt} := R_{dl} + (N_{rd} - 2)R_d + R_{dh}$$

$$R_{dt} = 1.053\,G\Omega$$

Trace voltages, actual, are now:

$$V_{da}(i_d) := (V_{dh} - V_{dl}) \cdot \frac{[R_{dl} + R_d \cdot (i_d - 1)]}{R_{dt}} + V_{dl}$$

$$V_{da}(i_d) = \begin{pmatrix} -16.296 \\ -14.823 \\ -13.351 \\ -11.878 \\ -10.405 \\ -8.933 \\ -7.46 \\ -5.988 \\ -4.515 \\ -3.043 \\ -1.571 \\ -0.098 \\ 1.375 \\ 2.847 \\ 4.32 \\ 5.792 \\ 7.265 \end{pmatrix} kV \quad \text{compare -->} \quad V_d(i_d) = \begin{pmatrix} -16.296 \\ -14.823 \\ -13.351 \\ -11.878 \\ -10.406 \\ -8.933 \\ -7.46 \\ -5.988 \\ -4.516 \\ -3.043 \\ -1.571 \\ -0.098 \\ 1.375 \\ 2.847 \\ 4.319 \\ 5.792 \\ 7.265 \end{pmatrix} kV$$

$$\Delta V_d := V_d(2) - V_d(1) \qquad \Delta V_d = 1.472\,kV$$

$$\Delta V_{dl} := V_d(1) - V_{dl} \qquad \Delta V_{dl} = 3.704\,kV$$

$$\Delta V_{dh} := V_{dh} - V_d(17) \qquad \Delta V_{dh} = 3.735\,kV$$

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.

Current: $$I_d := \frac{V_{dh} - V_{dl}}{R_{dt}} \qquad I_c = -0.029\,mA$$

Power: $$P_d := \frac{(V_{dh} - V_{dl})^2}{R_{dt}} \qquad P_d = 0.913\,W$$

Power per resistor

intertrace	low	high
$P_{rd} := I_d{}^2 R_d$	$P_{rdl} := I_d{}^2 R_{dl}$	$P_{rdh} := I_d{}^2 R_{dh}$
$P_{rd} = 0.043\,W$	$P_{rdl} = 0.109\,W$	$P_{rdh} = 0.11\,W$

Trace to trace gap:

$z_{tt} = 0.07\,cm$

Trace to trace voltage gradient

$$E_d := \frac{V_d(2) - V_d(1)}{z_{tt}} \qquad E_d = 21.036\,\frac{kV}{cm} \qquad E_d = 53.4\,\frac{kV}{in}$$

Mesh frame to trace distances:

$g_{dl} := 0.2cm$ $\qquad g_{dh} := 0.2cm$

Mesh frame to trace voltage gradients

$$E_{dl} := \frac{V_d(1) - V_{dl}}{g_{dl}} \qquad E_{dl} = 18.5\,\frac{kV}{cm}$$

$$E_{dh} := \frac{V_{dh} - V_d(17)}{g_{dh}} \qquad E_{dh} = 18.7\,\frac{kV}{cm}$$

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

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

Mesh positions along axis

$z_{al} := 0cm$ (baseline) $\qquad z_{ah} := 5cm$

First trace centerline position

$z_{a0} := .976cm$

There are 9 traces, and thus 10 resistors (2 end resistors and 8 intertrace resistors):

trace number:

$i_a := 1, 2..9$

trace centerline position:

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

$$z_a(i_a) = \begin{pmatrix} 0.976 \\ 1.356 \\ 1.736 \\ 2.116 \\ 2.496 \\ 2.876 \\ 3.256 \\ 3.636 \\ 4.016 \end{pmatrix} cm$$

trace voltages

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

$$V_a(i_a) = \begin{pmatrix} 16.096 \\ 14.576 \\ 13.056 \\ 11.536 \\ 10.016 \\ 8.496 \\ 6.976 \\ 5.456 \\ 3.936 \end{pmatrix} kV$$

Max power, per panel

$P_{max} = 1\,W$

Min resistance total:

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

Number of resistors (assume all same for start)

$N_{ra} := 10$

Intertrace resistance, minimum:

$$R_{a\_min} := \frac{R_{ta}}{N_{ra}} \qquad R_{a\_min} = 40\,M\Omega$$

Choose intertrace resistor value:

$R_a := 50M\Omega$

End resistor values:

$$R_{al} := R_a \cdot \frac{z_{a0}}{p_{sl}} \qquad R_{al} = 128.4\,M\Omega$$ low side, z_a= 0 cm

$$R_{ah} := R_a \cdot \frac{(z_{ah} - z_a(9))}{p_{sl}} \qquad R_{ah} = 129.5\,M\Omega$$ high side z_a = 5 cm

total initial resistance:

$$R_{at} := R_{al} + 8 \cdot R_a + R_{ah} \qquad R_{at} = 657.9\,M\Omega$$

trace voltages, actual, are now:

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

$$V_{a\_a}(i_a) = \begin{pmatrix} 16.096 \\ 14.576 \\ 13.056 \\ 11.536 \\ 10.016 \\ 8.496 \\ 6.976 \\ 5.456 \\ 3.936 \end{pmatrix} kV \quad \text{compare -->} \quad V_a(i_a) = \begin{pmatrix} 16.096 \\ 14.576 \\ 13.056 \\ 11.536 \\ 10.016 \\ 8.496 \\ 6.976 \\ 5.456 \\ 3.936 \end{pmatrix} kV$$

$$\Delta V_a := V_a(1) - V_a(2) \qquad \Delta V_a = 1.52\,kV$$

$$\Delta Val := V_{al} - V_a(1) \qquad \Delta Val = 3.904\,kV$$

$$\Delta V_{ah} := V_a(9) - V_{ah} \qquad \Delta V_{ah} = 3.936\,kV$$

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.

Current: $$I_a := \frac{V_{ah} - V_{al}}{R_{at}} \qquad I_a = -0.03\,mA$$

Power: $$P_a := \frac{(V_{ah} - V_{al})^2}{R_{at}} \qquad P_a = 0.608\,W$$

Power per resistor

intertrace low high

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

$$P_{ra} = 0.046\,W \qquad P_{ral} = 0.119\,W \qquad P_{rah} = 0.12\,W$$

Trace to trace gap:

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

Trace to trace voltage gradient

$$E_a := \frac{V_a(1) - V_a(2)}{z_{tt}} \qquad E_a = 21.714\,\frac{kV}{cm} \qquad E_a = 55.2\,\frac{kV}{in}$$

Mesh frame to trace distances:

$$g_{al} := 0.22cm \qquad g_{ah} := 0.22cm$$

Mesh frame to trace voltage gradients

$$E_{al} := \frac{V_{al} - V_a(1)}{g_{al}} \qquad E_{al} = 17.7\,\frac{kV}{cm}$$

$$E_{ah} := \frac{V_a(9) - V_{ah}}{g_{ah}} \qquad E_{ah} = 17.9\,\frac{kV}{cm}$$

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

$$E_{tr\_TPC} = 94.5\,\frac{kV}{cm}$$

Total power:

$$P_t := 6\left(P_c + P_d + P_a\right) \qquad P_t = 12.418\,W$$