APPENDIX A

2ND-ORDER CURRENT IMPULSE CIRCUIT

A lightning impulse combination generator available at the University of the Witwatersrand (Melaia, 1993), may be configured for current mode only (refer to Figure A1).

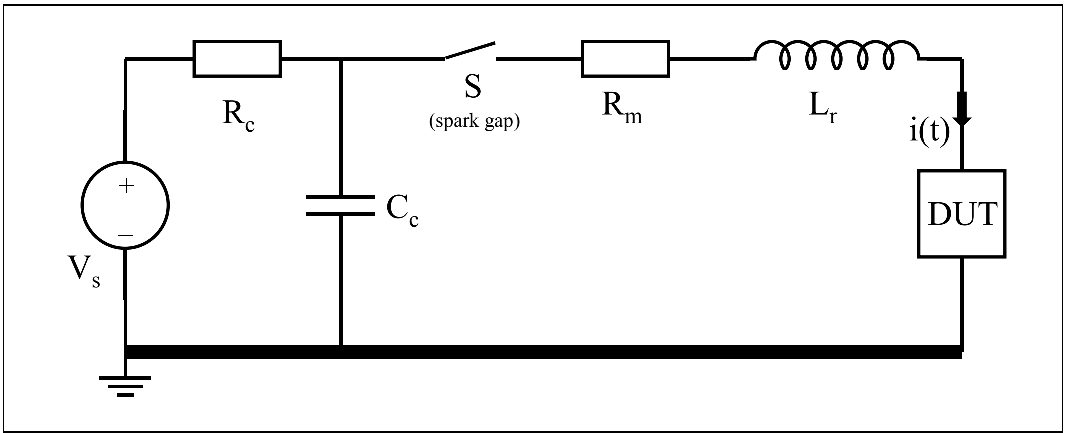


Figure A1: 2^{nd}-order impulse circuit (combination generator in current mode)

In the charging loop a dc voltage source V_s charges the charging capacitor C_c via series resistor R_c. In the discharging loop, C_c is discharged via switch S into resistor R_m, inductor L_r and the device-under-test (DUT).

The waveform parameters (e.g. 8/20 µs) are defined under short-circuit conditions i.e. DUT replaced by a shunt. Therefore the discharging loop comprises a 2^{nd}-order RLC circuit described by:

$$\frac{d^2 i}{dt^2} + 2\alpha \frac{di}{dt} + \omega_n^2 i = 0 \tag{A1}$$

where

$$\alpha = \frac{R_m}{2L_r} \qquad \omega_n = \frac{1}{\sqrt{L_r C_c}}$$

For an under-damped circuit, $\alpha < \omega_n$ and:

$$\frac{i(t)}{I} = k\exp(-\alpha t)\sin(\omega_d t) \tag{A2}$$

where

$$k = \frac{\exp(\alpha t_{peak})}{\sin(\omega_d t_{peak})} \qquad \omega_d = \sqrt{\omega_n^2 - \alpha^2} \qquad t_{peak} = \frac{\tan^{-1}(\omega_d / \alpha)}{\omega_d}$$

For a critically damped circuit, $\alpha = \omega_n$ and:

$$\frac{i(t)}{I} = k\,t\exp(-\alpha t) \tag{A3}$$

where

$$k = \frac{\exp(\alpha t_{peak})}{t_{peak}} \qquad t_{peak} = \frac{1}{\alpha}$$

For an over-damped circuit, $\alpha > \omega_n$ and:

$$\frac{i(t)}{I} = k(\exp(s_1 t) - \exp(s_2 t)) \tag{A4}$$

where

$$s_1 = -\alpha - \sqrt{\alpha^2 - \omega_n^2} \qquad k = \{\exp(s_1 t_{peak}) - \exp(s_2 t_{peak})\}^{-1} \qquad t_{peak} = \frac{\ln(s_1/s_2)}{s_2 - s_1}$$
$$s_2 = -\alpha + \sqrt{\alpha^2 - \omega_n^2}$$

By plotting the resulting equations (A2, A3 and A4) in Microsoft® Excel (or similar package), α and ω_n are adjusted through a number of iterations until the 0.1, 0.9 and 0.5 criteria are met satisfactorily by one of the equations.

APPENDIX B

DERIVING R_{sys} & L_{sys}

Consider the combination generator in current mode, as per Appendix A, but where R_m and L_r have been replaced by a shunt, and the device-under-test (DUT) has also been replaced by a shunt. The resulting circuit is shown in Figure B1, where R_{sys} and L_{sys} are the lumped system resistance and inductance respectively in the discharging loop.

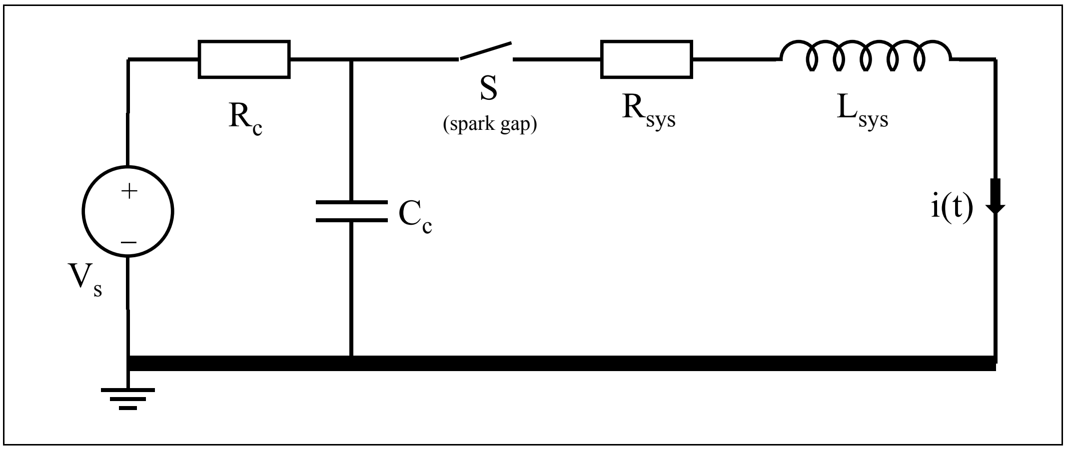


Figure B1: Impulse generator (Figure A1) with R_m, L_r and DUT replaced by shunts

The discharging loop comprises an under-damped 2nd-order RLC circuit, producing a waveform shown in Figure B2 and described by:

$$\frac{i(t)}{I} = k \exp(-\alpha\, t) \sin(\omega_d t) \qquad \text{(B1)}$$

where

$$k = \frac{\exp(\alpha\, t_{peak})}{\sin(\omega_d t_{peak})} \qquad \omega_d = \sqrt{\omega_n^2 - \alpha^2} \qquad t_{peak} = \frac{\tan^{-1}(\omega_d / \alpha)}{\omega_d}$$

and

$$\alpha = \frac{R_{sys}}{2L_{sys}} \qquad \omega_n = \frac{1}{\sqrt{L_{sys} C_c}}$$

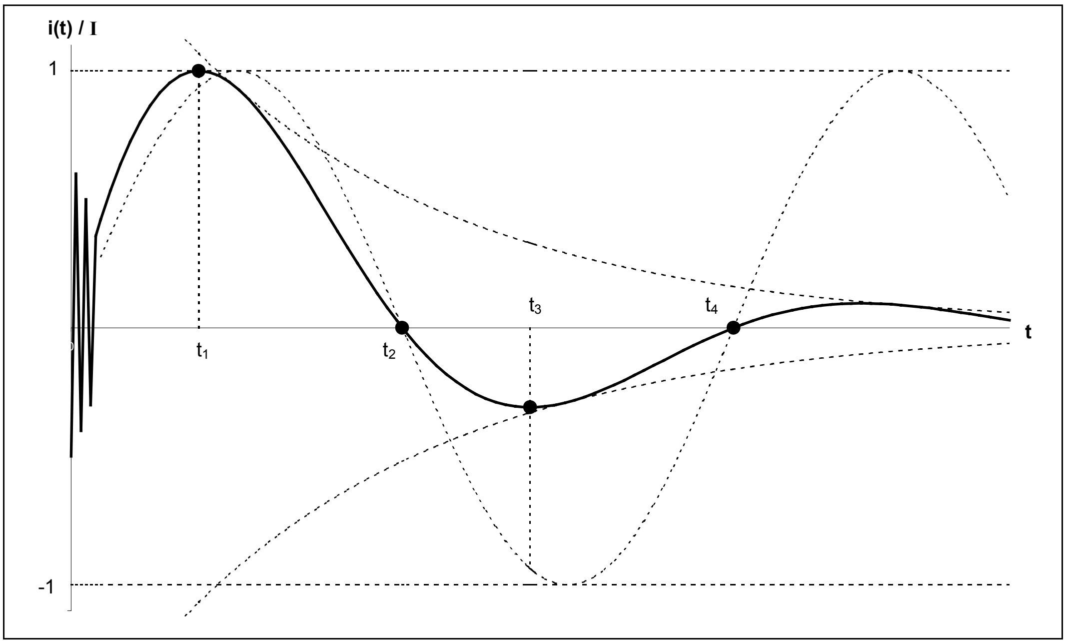


Figure B2: Under-damped current waveform

Because C_c is known, R_{sys} and L_{sys} may be calculated once values for α and ω_d have been derived from the recorded waveform. Yet in practice the exact origin of the waveform on the oscilloscope trace is seldom known (also due to noise), hence the absolute values of t_1, t_2, t_3 and t_4 are unknown. But their relative positions e.g. $t_2 - t_1$ can easily be deduced from the recorded waveform, using the oscilloscope cursor function, provided the waveform is sufficiently under-damped such that the peaks and zeros are easily discernible. Similarly the ratio $i(t_1) : i(t_3)$ can easily be deduced and calculated using the oscilloscope cursor function.

Therefore, according to equation (B1), $i(t) = 0$ when $\sin(\omega_d t) = 0$ i.e. when $\omega_d t = 0$, π, 2π, … etc., and from Figure B2, $\omega_d t_2 = \pi$ and $\omega_d t_4 = 2\pi$. Therefore:

$$\omega_d = \frac{\pi}{t_4 - t_2} \tag{B2}$$

Also from Figure B2 and equation (B1):

$$\frac{i(t_1)}{I} = k \exp(-\alpha t_1) \sin(\omega_d t_1) \tag{B3}$$

and

$$\frac{i(t_3)}{I} = k\ \exp(-\alpha t_3)\ \sin(\omega_d t_3) \qquad \text{(B4)}$$

Dividing equation (B3) by (B4), and solving for α yields:

$$\alpha \ = \ \frac{\ln\left(\dfrac{i(t_1)\ \sin(\omega_d t_3)}{i(t_3)\ \sin(\omega_d t_1)}\right)}{t_3 - t_1} \qquad \text{(B5)}$$

But the peaks of the curve in Figure B2 occur when the derivative of equation (B1) is zero, as follows:

$$\frac{d}{dt}\left(\frac{i(t)}{I}\right) \ = \ k\exp(-\alpha t)[\omega_d\ \cos(\omega_d t) - \alpha\sin(\omega_d t)] \ = \ 0$$

This holds when $\tan(\omega_d t) = \omega_d/\alpha$ yielding $\omega_d t = \tan^{-1}(\omega_d/\alpha)$, $\pi + \tan^{-1}(\omega_d/\alpha)$, … etc. Therefore from Figure B2, $\omega_d t_1 = \tan^{-1}(\omega_d/\alpha)$ and $\omega_d t_3 = \pi + \tan^{-1}(\omega_d/\alpha) = \pi + \omega_d t_1$. Hence:

$$\frac{\sin(\omega_d t_3)}{\sin(\omega_d t_1)} \ = \ \frac{\sin(\pi + \omega_d t_1)}{\sin(\omega_d t_1)} \ = \ -1$$

and equation (B5) reduces to:

$$\alpha \ = \ \frac{\ln\left(\dfrac{i(t_1)}{-i(t_3)}\right)}{t_3 - t_1} \qquad \text{(B6)}$$

Therefore once ω_d and α have been calculated from the recorded waveform as per equations (B2) and (B6), ω_n, R_{sys} and L_{sys} may be calculated.

APPENDIX C

R_{stray} & L_{stray} DATA PER CAPACITOR CONFIGURATION

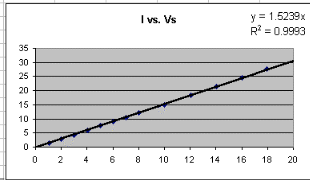
See overleaf.

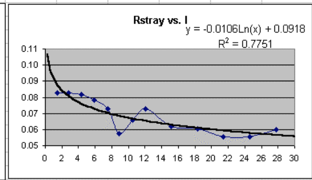
Table C1: R_{stray} & L_{stray} data per capacitor configuration

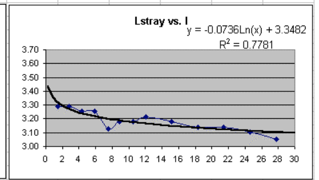
Rshunt = 0.001 ohm
Lshunt = 0.15 uH

Cc = 8.47 uF

Impulse No.	Vs (kV)	I (kA)	I/Vs (kA/kV)	1/wn (us)	1/alpha (us)	Rsys (ohm)	Lsys (uH)	Rstray (ohm)	Lstray (uH)
1	1.055	1.480	1.40	5.40	82.43	0.0835	3.44	0.0825	3.29
2	2.004	2.820	1.41	5.40	82.42	0.0835	3.44	0.0825	3.29
3	3.007	4.360	1.45	5.37	82.38	0.0826	3.40	0.0816	3.25
4	4.020	5.880	1.46	5.37	85.80	0.0793	3.40	0.0783	3.25
5	5.040	7.480	1.48	5.27	88.98	0.0737	3.28	0.0727	3.13
6	6.040	8.900	1.47	5.31	113.90	0.0584	3.33	0.0574	3.18
7	7.030	10.500	1.49	5.31	99.20	0.0671	3.33	0.0661	3.18
8	8.020	12.100	1.51	5.34	91.33	0.0737	3.37	0.0727	3.22
9	10.030	15.100	1.51	5.31	106.05	0.0628	3.33	0.0618	3.18
10	12.080	18.300	1.51	5.28	107.02	0.0615	3.29	0.0605	3.14
11	14.030	21.400	1.53	5.28	116.24	0.0566	3.29	0.0556	3.14
12	16.010	24.600	1.54	5.25	114.81	0.0567	3.25	0.0557	3.10
13	17.980	27.800	1.55	5.21	105.57	0.0607	3.20	0.0597	3.05
AVERAGE			1.49	5.32	98.16	0.0692	3.33	0.0682	3.18
STD DEV			0.05	0.06	13.15	0.0106	0.07	0.0106	0.07

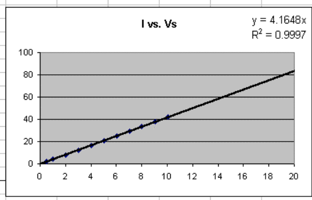


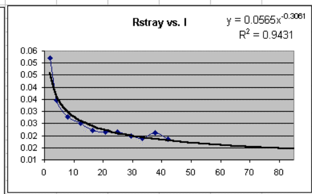


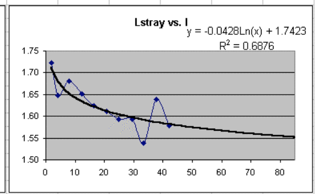


Cc = 33.93 uF

Impulse No.	Vs (kV)	I (kA)	I/Vs (kA/kV)	1/wn (us)	1/alpha (us)	Rsys (ohm)	Lsys (uH)	Rstray (ohm)	Lstray (uH)
1	0.525	2.000	3.81	7.97	70.65	0.0530	1.87	0.0520	1.72
2	1.003	4.000	3.99	7.81	100.93	0.0356	1.80	0.0346	1.65
3	2.022	8.000	3.96	7.88	126.84	0.0289	1.83	0.0279	1.68
4	3.036	12.400	4.08	7.82	137.59	0.0262	1.80	0.0252	1.65
5	4.011	16.400	4.09	7.76	152.95	0.0232	1.77	0.0222	1.62
6	5.000	20.800	4.16	7.73	156.66	0.0225	1.76	0.0215	1.61
7	6.030	25.000	4.15	7.69	154.36	0.0226	1.74	0.0216	1.59
8	7.040	29.400	4.18	7.69	166.84	0.0209	1.74	0.0199	1.59
9	8.010	33.400	4.17	7.57	169.90	0.0199	1.69	0.0189	1.54
10	9.040	37.600	4.16	7.79	160.68	0.0223	1.79	0.0213	1.64
11	10.050	42.200	4.20	7.66	177.19	0.0195	1.73	0.0185	1.58
AVERAGE			4.09	7.76	143.14	0.0268	1.78	0.0258	1.63
STD DEV			0.12	0.11	32.38	0.0099	0.05	0.0099	0.05

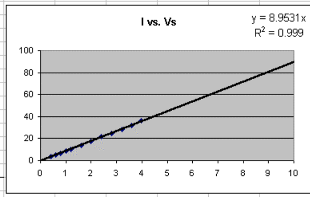


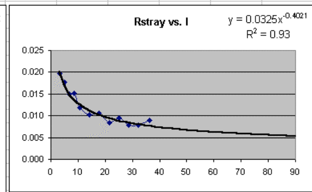


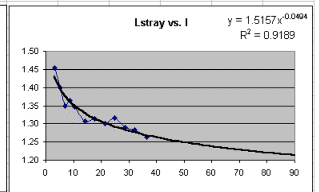


Cc = 136.00 uF

Impulse No.	Vs (kV)	I (kA)	I/Vs (kA/kV)	1/wn (us)	1/alpha (us)	Rsys (ohm)	Lsys (uH)	Rstray (ohm)	Lstray (uH)
1	0.407	3.300	8.11	14.77	154.55	0.0208	1.60	0.0198	1.45
2	0.603	5.080	8.42	14.52	165.51	0.0187	1.55	0.0177	1.40
3	0.803	6.840	8.52	14.28	186.98	0.0160	1.50	0.0150	1.35
4	1.007	8.700	8.64	14.35	187.23	0.0162	1.51	0.0152	1.36
5	1.202	10.500	8.74	14.27	233.98	0.0128	1.50	0.0118	1.35
6	1.602	14.100	8.80	14.08	259.38	0.0112	1.46	0.0102	1.31
7	2.003	17.700	8.84	14.11	253.19	0.0116	1.46	0.0106	1.31
8	2.410	21.400	8.88	14.05	310.92	0.0093	1.45	0.0083	1.30
9	2.803	25.000	8.92	14.12	280.41	0.0105	1.47	0.0095	1.32
10	3.206	28.600	8.92	13.99	325.58	0.0088	1.44	0.0078	1.29
11	3.605	32.200	8.93	13.96	327.19	0.0088	1.43	0.0078	1.28
12	3.970	36.400	9.17	13.86	282.84	0.0100	1.41	0.0090	1.26
AVERAGE			8.74	14.20	247.31	0.0129	1.48	0.0119	1.33
STD DEV			0.28	0.26	61.65	0.0041	0.05	0.0041	0.05

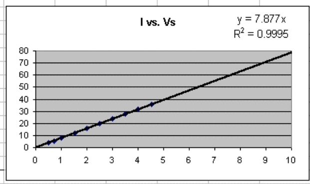


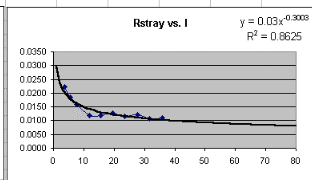


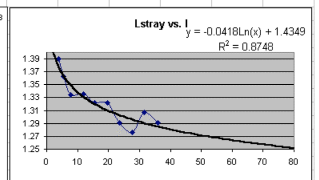


Cc = 102.30 uF

Impulse No.	Vs (kV)	I (kA)	I/Vs (kA/kV)	1/wn (us)	1/alpha (us)	Rsys (ohm)	Lsys (uH)	Rstray (ohm)	Lstray (uH)
1	0.514	3.760	7.32	12.55	131.61	0.0234	1.54	0.0224	1.39
2	0.726	5.440	7.49	12.44	154.08	0.0196	1.51	0.0186	1.36
3	1.008	7.680	7.62	12.32	175.93	0.0169	1.48	0.0159	1.33
4	1.540	11.800	7.66	12.33	233.21	0.0127	1.49	0.0117	1.34
5	2.002	15.600	7.79	12.27	229.87	0.0128	1.47	0.0118	1.32
6	2.504	19.600	7.83	12.27	213.19	0.0138	1.47	0.0128	1.32
7	3.006	23.600	7.85	12.14	228.38	0.0126	1.44	0.0116	1.29
8	3.506	27.600	7.87	12.08	216.51	0.0132	1.43	0.0122	1.28
9	4.003	31.600	7.89	12.21	252.10	0.0116	1.46	0.0106	1.31
10	4.520	36.000	7.96	12.14	242.30	0.0119	1.44	0.0109	1.29
AVERAGE			7.73	12.28	207.72	0.0149	1.47	0.0139	1.32
STD DEV			0.20	0.14	40.17	0.0039	0.03	0.0039	0.03







APPENDIX D

LOW RESISTANCE SHUNTS – MORE CONSIDERATIONS

Low resistance shunts may be constructed to achieve very low inductance, using an alternative conductor to Nichrome e.g. Copper, Aluminium or Iron; these shunts would typically be thin but broad to keep the inductance as low as possible – refer to Figure D1.

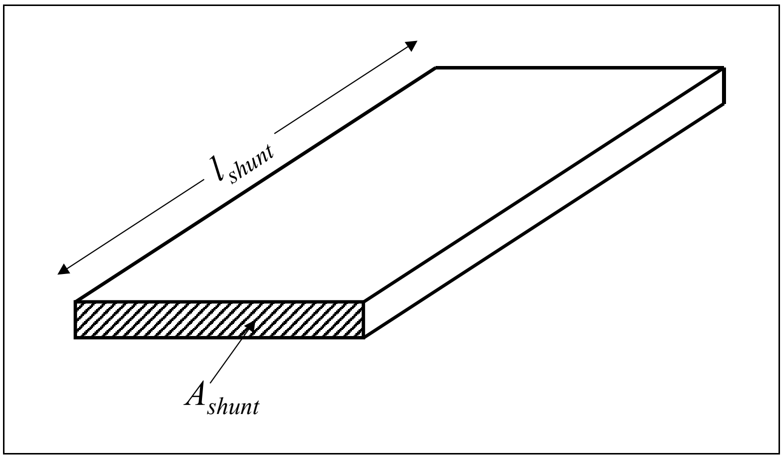


Figure D1: Low resistance shunt geometry

However Copper, Aluminium and Iron are wholly unsuitable conductors for the purposes of the very low inductance shunts i.e. l_{shunt} is excessive in all cases to achieve the associated resistance values required in this work. This is due to resistivity ρ that is too low, and a higher component mass m that is required to compensate for relatively high temperature coefficient α_T. Whilst Nichrome is superior in this regard i.e. l_{shunt} is much smaller in all cases, it is also unsuitable for the purposes of very low inductance shunts.

<u>Graphite</u>

A more appropriate material would allow a small component mass m such that its dimensions, particularly length l_{shunt}, are small. This would require high resistivity ρ, as well as low temperature coefficient α_T and/or high heat capacity c. An example of such material is graphite with the following properties:

α_T = -0.0005 °C^{-1} (Giancoli, 1984); c = 709 J/kg.°C (Counterman, 1997a);
ρ = 3e-5 to 60e-5 Ω.m (Giancoli, 1984); P = 2260 kg/m^3 (Counterman, 1997b).

Assuming a maximum permissible $\Delta R/R_0$ of 5%, Table D1 shows the resultant ΔT_{max} and hence the required graphite component mass per C_c. Table D2 shows the shunt lengths for each of the very low inductance components required.

Table D1: Required (minimum) m for graphite

C_c (μF)	$V_{s,max}$ (kV)	ΔT_{max} (°C)	m (kg)
8.47	20	100.0	0.024
33.93	20		0.096
136.0	10		0.096

Table D2: Required l_{shunt} and A_{shunt} for graphite

R (Ω)	l_{shunt} (m)	A_{shunt} (mm^2)
0.035	0.05 – 0.22	853.3 – 190.8
0.335	0.15 – 0.69	275.8 – 61.7
0.487	0.19 – 0.83	228.8 – 51.2
0.650	0.21 – 0.96	198.0 – 44.3

Certainly these l_{shunt} values are workable, particularly the lower ones per range, although the performance of the graphite under high impulse current would need to be explored.

Immersion in high heat capacity fluid

An alternative solution is to reduce the length of the shunt, without reducing its (thermal) mass, by immersing it in a non-conducting tube[1] of distilled water or any other very low (electrical) conductivity fluid with high heat capacity – refer to Figure D2.

As before, closure of spark gap S will result in the energy stored in capacitor C_c dissipating as heat energy in R_m under short-circuit conditions. The worst case occurs for $V_{s,max}$:

[1] Square tubing would be more applicable but cylindrical tubing is more commonly available.

$$\frac{1}{2} C_c V_{s,\max}^2 = m c \Delta T_{\max} + m_f \, c_f \, \Delta T_{\max} \tag{D1}$$

where m is the mass (kg) and c is the heat capacity (J/kg.°C) of the shunt, m_f is the mass (kg) and c_f is the heat capacity (J/kg.°C) of the fluid, and ΔT_{max} is the maximum temperature change (°C) of the component.

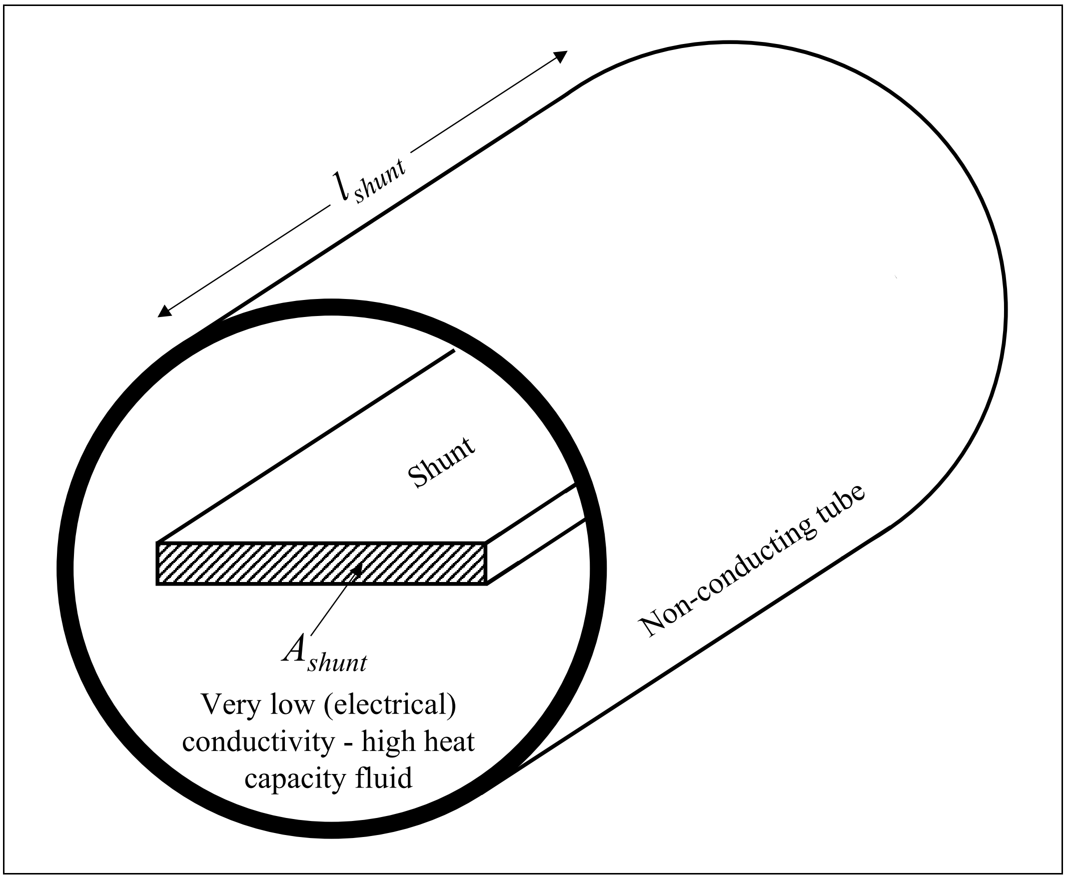


Figure D2: Shunt in very low (electrical) conductivity / high heat capacity fluid

Equation (D1) does not account for dynamic heat flow – the fluid temperature will not rise quickly due to its low thermal conductivity compared to the metallic shunt.

This may be improved by increasing the shunt vs. fluid contact area i.e. by using a number of uniformly-spaced parallel strands of wire e.g. Nichrome resistance wire – refer to Figure D3. Each strand is enclosed by an imaginary cylinder of sufficient fluid volume (diameter d_f) to limit the increase in temperature of the strand and imaginary cylinder to ΔT_{max}.

It is assumed that any fluid beyond the imaginary cylinder has no influence in limiting ΔT_{max} due to the relatively low thermal conductivity of the fluid. This yields a minimum strand spacing a_s and hence inner diameter D_t of the tube.

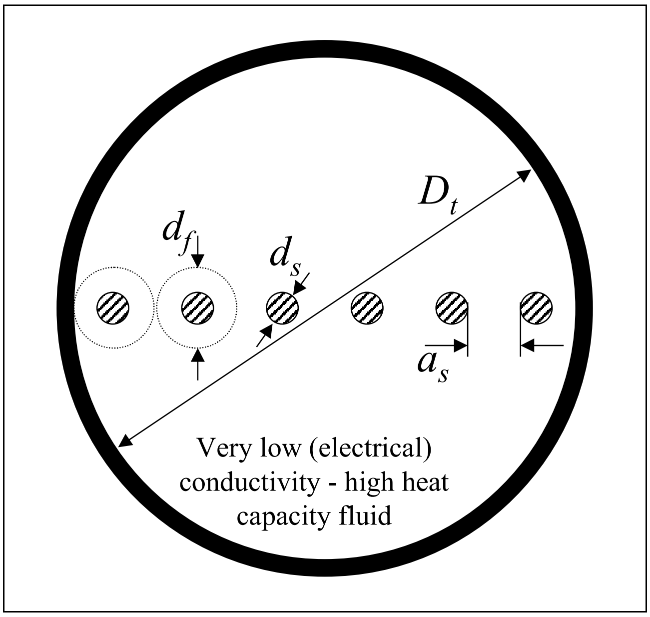


Figure D3: Tube cross-section with uniformly spaced wire strands in fluid

Therefore rearranging equation (D1) and substituting for mass yields:

$$D_t = s(a_s + d_s) = s\,d_f = s\sqrt{\frac{2C_c V_{s,\max}^2}{\pi \mathrm{P}_f\, c_f\, s\, l_s\, \Delta T_{\max}} + d_s^2\left(1 - \frac{\mathrm{P}c}{\mathrm{P}_f\, c_f}\right)} \qquad \text{(D2)}$$

where P_f is the fluid density (kg/m^3), P is the conductor density (kg/m^3), l_s is the strand length (m), d_s is the strand diameter (m), and s is the number of strands.

Unless the resistance of the shunt is required to be very low i.e. R < 0.01 Ω, the available Nichrome wire is best used. The first step is to define the maximum allowable l_s such that the shunt can fit comfortably between the terminals. Then for each reel, assume maximum l_s and calculate the number of strands s to yield the required R. Round s down to the nearest integer and calculate the actual (reduced) l_s per reel. Choose the reel yielding l_s closest to the maximum allowable value, whilst ensuring that s is suitably high i.e. $s \geq 4$ to ensure effective heat transfer and low inductance. Then choose a suitable fluid, and substitute for the various variables in equation (D2) to yield D_t.

Example 1: Require R = 0.035 Ω. Terminal spacing is approximately 0.1 m; this defines the maximum allowable l_s. Choosing distilled water[2], and bearing in mind that the water must not be allowed to boil, conservatively choose ΔT_{max} = 75 °C. Table D3 shows the results per Nichrome wire reel, including D_t as per equation (D2).

Table D3: Example 1: Results per Nichrome wire reel

REEL	d_s (mm)	R' (Ω/m)	s	l_s (m)	D_t (mm)
1	1.1	0.51	1	0.069	20.1
2	0.914	0.714	2	0.098	23.7
3	0.9	0.79	2	0.089	25.0
4	1.219	0.924	2	0.076	27.0
5	0.813	0.947	2	0.074	27.3
6	1.219	0.98	2	0.071	27.8
7	0.71	1.292	3	0.081	31.9
8	0.914	1.68	4	0.083	36.4
9	0.56	2.004	5	0.087	39.8
10	**0.45**	**3.187**	**9**	**0.099**	**50.2**
11	0.4	3.95	11	0.097	55.9
12	0.315	14.1	40	0.099	105.6
13	0.213	14.39	41	0.100	106.6
14	0.193	36.5	104	0.100	169.9

R = 0.035 Ω is achieved for all reels. Typically reels 8 to 11 would be suitable i.e. $s \geq 4$, with reel 10 the optimum choice because l_s is maximised; thereafter s becomes too large to be practicable.

Example 2: Require R = 0.650 Ω. Again terminal spacing is approximately 0.1 m; this defines the maximum allowable l_s. Choosing distilled water, and bearing in mind that the water must not be allowed to boil, conservatively choose

[2] Water: P_f = 1000 kg/m^3 (Giancoli, 1984); c_f = 4180 J/kg.°C (Counterman, 1997a).
Nichrome: P = 7800 kg/m^3 i.e. assumed same as Iron (Giancoli, 1984); $c \approx$ 447 J/kg.°C i.e. assumed average of Iron (450), Nickel (444) and Chrome (449) (Counterman, 1997a).

ΔT_{max} = 75 °C. Table D4 shows the results per Nichrome wire reel, including D_t as per equation (D2).

Table D4: Example 2: Results per Nichrome wire reel

REEL	d_s (mm)	R' (Ω/m)	s	l_s (m)	D_t (mm)
10	0.45	3.187	0	-	-
11	0.4	3.95	0	-	-
12	0.315	14.1	2	0.092	24.5
13	0.213	14.39	2	0.090	24.7
14	**0.193**	**36.5**	**5**	**0.089**	**39.4**

R = 0.650 Ω cannot be achieved for reels 1 to 11. Only reel 14 is suitable because $s \geq 4$.

The above considerations would need to be explored further.

APPENDIX E

s & l_s CALCULATIONS FOR SIX COMPONENTS

<u>Component 1: 8/20 µs</u> (C_c = 8.47 µF, R = 0.607, L = 4.2 µH)

Choose lowest s, then lowest l_s; refer to Table E1 where optimum selection is shown in bold. Experimentation led to doubling up of s and l_s to effect a loosely packed solenoid to increase inductance.

Table E1: Component 1: Nichrome reel data sorted by s then l_s

REEL	d_s (mm)	R' (Ω/m)	s	l_s (mm)
1	**1.1**	**0.51**	**2**	**2.380**
2	0.914	0.714	3	2.550
3	0.9	0.79	3	2.305
4	1.219	0.924	3	1.971
5	1.219	0.98	3	1.858
6	0.813	0.947	4	2.564
7	0.71	1.292	5	2.349
8	0.914	1.68	5	1.807
9	0.56	2.004	8	2.423
10	0.45	3.187	12	2.286
11	0.4	3.95	15	2.305
12	0.315	14.1	34	1.464
13	0.213	14.39	51	2.151
14	0.193	36.5	89	1.480

<u>Component 2: 8/20 μs</u> (C_c = 33.93 μF, R = 0.149, L = 0.3 μH)

Choose lowest l_s for even-numbered s; refer to Table E2 where optimum selection is shown in bold. Effect anti-parallel strand loops to minimise inductance.

Table E2: Component 2: Nichrome reel data sorted by l_s

REEL	d_s (mm)	R' (Ω/m)	l_s (mm)	s
12	0.315	14.1	1.458	138
14	0.193	36.5	1.474	361
8	0.914	1.68	1.508	17
6	**1.219**	**0.98**	**1.520**	**10**
4	1.219	0.924	1.613	10
13	0.213	14.39	2.133	206
10	0.45	3.187	2.151	46
11	0.4	3.95	2.188	58
7	0.71	1.292	2.191	19
5	0.813	0.947	2.203	14
9	0.56	2.004	2.231	30
3	0.9	0.79	2.263	12
2	0.914	0.714	2.296	11
1	1.1	0.51	2.337	8

<u>Component 3: 8/20 µs</u> (C_c = 136.0 µF, R = 0.035, L = 0 µH)

Choose lowest l_s for even-numbered s, but avoid high s because numerous thin strands of wire are not workable; refer to Table E3 where optimum selection is shown in bold. Note that odd s is not viewed as critical because it is quite high. Effect anti-parallel strand loops to minimise inductance.

Table E3: Component 3: Nichrome reel data sorted by l_s

REEL	d_s (mm)	R' (Ω/m)	l_s (mm)	s
6	1.219	0.98	0.643	21
12	0.315	14.1	0.651	306
8	**0.914**	**1.68**	**0.661**	**37**
14	0.193	36.5	0.661	804
4	1.219	0.924	0.682	21
13	0.213	14.39	0.953	457
10	0.45	3.187	0.960	102
11	0.4	3.95	0.972	128
9	0.56	2.004	0.973	65
7	0.71	1.292	0.975	42
5	0.813	0.947	0.982	31
3	0.9	0.79	0.987	26
1	1.1	0.51	1.000	17
2	0.914	0.714	1.008	24

<u>Component 4: 4/70 µs</u> (C_c = 8.47 µF, R = 10.479, L = 15.3 µH)

Choose lowest s, then lowest l_s; refer to Table E4 where optimum selection is shown in bold. Effect loosely packed solenoid to increase inductance.

Table E4: Component 4: Nichrome reel data sorted by s then l_s

REEL	d_s (mm)	R' (Ω/m)	s	l_s (mm)
8	**0.914**	**1.68**	**1**	**6.238**
6	1.219	0.98	1	10.693
5	0.813	0.947	1	11.065
4	1.219	0.924	1	11.341
3	0.9	0.79	1	13.265
2	0.914	0.714	1	14.676
1	1.1	0.51	1	20.547
9	0.56	2.004	2	10.458
7	0.71	1.292	2	16.221
10	0.45	3.187	3	9.864
11	0.4	3.95	4	10.612
12	0.315	14.1	9	6.689
13	0.213	14.39	13	9.467
14	0.193	36.5	22	6.316

Component 5: 4/70 μs (C_c = 33.93 μF, R = 2.613, L = 3.0 μH)

Choose lowest l_s but avoid high s; refer to Table E5 where optimum selection is shown in bold. Effect bifilar winding to reduce inductance.

Table E5: Component 5: Nichrome reel data sorted by l_s

REEL	d_s (mm)	R' (Ω/m)	l_s (mm)	s
12	0.315	14.1	6.116	33
8	**0.914**	**1.68**	**6.221**	**4**
14	0.193	36.5	6.228	87
6	1.219	0.98	7.999	3
4	1.219	0.924	8.484	3
13	0.213	14.39	8.898	49
10	0.45	3.187	9.019	11
9	0.56	2.004	9.127	7
11	0.4	3.95	9.261	14
3	0.9	0.79	9.923	3
7	0.71	1.292	10.112	5
1	1.1	0.51	10.247	2
2	0.914	0.714	10.979	3
5	0.813	0.947	11.037	4

<u>Component 6: 4/70 µs</u> (C_c = 102.3 µF, R = 0.863, L = 0.2 µH)

Choose lowest l_s for even-numbered s, but avoid high s because numerous thin strands of wire are not workable; refer to Table E6 where optimum selection is shown in bold. Effect anti-parallel strand loops to minimise inductance.

Table E6: Component 6: Nichrome reel data sorted by l_s

REEL	d_s (mm)	R' (Ω/m)	l_s (mm)	s
12	0.315	14.1	3.060	50
14	0.193	36.5	3.074	130
8	**0.914**	**1.68**	**3.082**	**6**
6	1.219	0.98	3.522	4
4	1.219	0.924	3.736	4
13	0.213	14.39	4.438	74
5	0.813	0.947	4.556	5
11	0.4	3.95	4.588	21
10	0.45	3.187	4.603	17
7	0.71	1.292	4.676	7
9	0.56	2.004	4.737	11
2	0.914	0.714	4.835	4
1	1.1	0.51	5.076	3
3	0.9	0.79	5.462	5

APPENDIX F

QUANTIFICATION OF I vs. V_s PER COMPONENT

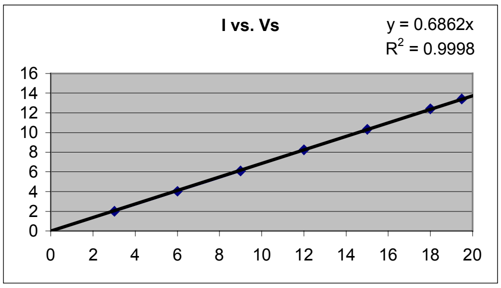
See overleaf.

Table F1: Quantification of I vs. V_s for components 1, 2, 4, 5 & 6

COMPONENT 1: 8/20 us

Cc = 8.47 uF

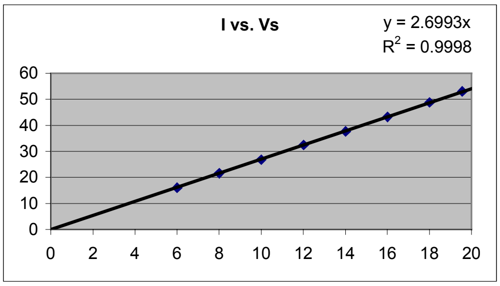
Impulse No.	Vs (kV)	I (kA)	I/Vs (kA/kV)	Twg (us)
1	3.014	2.000	0.6636	12.77
2	6.000	4.040	0.6733	12.59
3	9.000	6.080	0.6756	12.54
4	12.010	8.240	0.6861	12.35
5	15.010	10.320	0.6875	12.33
6	18.000	12.400	0.6889	12.30
7	19.500	13.400	0.6872	12.33
AVERAGE				12.46
STD DEV				0.18



COMPONENT 2: 8/20 us

Cc = 33.93 uF

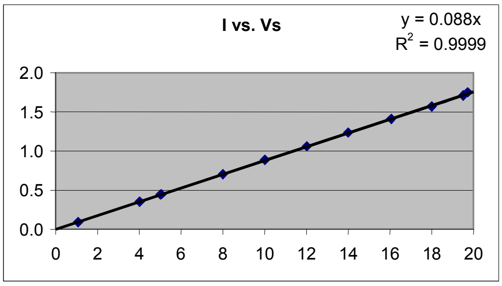
Impulse No.	Vs (kV)	I (kA)	I/Vs (kA/kV)	Twg (us)
1	6.010	16.000	2.6622	12.74
2	8.010	21.600	2.6966	12.58
3	10.000	26.800	2.6800	12.66
4	12.020	32.400	2.6955	12.59
5	14.010	37.600	2.6838	12.64
6	16.010	43.200	2.6983	12.57
7	18.010	48.800	2.7096	12.52
8	19.560	53.000	2.7096	12.52
AVERAGE				12.60
STD DEV				0.08



COMPONENT 4: 4/70 us

Cc = 8.47 uF

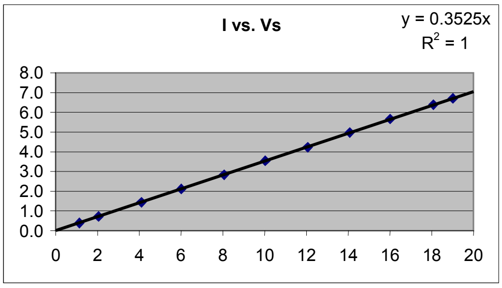
Impulse No.	Vs (kV)	I (kA)	I/Vs (kA/kV)	Twg (us)
1	1.072	0.092	0.0858	98.74
2	4.026	0.352	0.0874	96.92
3	5.020	0.444	0.0884	95.81
4	5.060	0.446	0.0881	96.14
5	8.010	0.704	0.0879	96.42
6	10.020	0.888	0.0886	95.62
7	12.020	1.060	0.0882	96.09
8	14.000	1.236	0.0883	95.98
9	16.060	1.410	0.0878	96.52
10	18.000	1.570	0.0872	97.15
11	19.510	1.710	0.0876	96.68
12	19.730	1.750	0.0887	95.54
AVERAGE				96.47
STD DEV				0.87



COMPONENT 5: 4/70 us

Cc = 33.93 uF

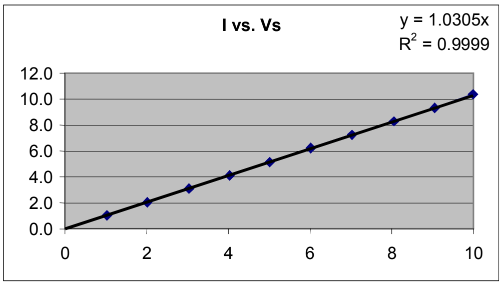
Impulse No.	Vs (kV)	I (kA)	I/Vs (kA/kV)	Twg (us)
1	1.129	0.386	0.3419	99.24
2	2.049	0.708	0.3455	98.20
3	4.100	1.430	0.3488	97.28
4	6.010	2.110	0.3511	96.64
5	8.060	2.830	0.3511	96.63
6	10.030	3.540	0.3529	96.14
7	12.060	4.220	0.3499	96.97
8	14.080	4.980	0.3537	95.93
9	16.020	5.660	0.3533	96.04
10	18.080	6.380	0.3529	96.15
11	19.010	6.700	0.3524	96.27
AVERAGE				96.86
STD DEV				1.03



COMPONENT 6: 5/72 us

Cc = 102.30 uF

Impulse No.	Vs (kV)	I (kA)	I/Vs (kA/kV)	Twg (us)
1	1.029	1.028	0.9990	102.40
2	2.013	2.030	1.0084	101.44
3	3.036	3.090	1.0178	100.51
4	4.026	4.100	1.0184	100.45
5	5.010	5.140	1.0259	99.71
6	6.020	6.220	1.0332	99.01
7	7.030	7.240	1.0299	99.33
8	8.050	8.280	1.0286	99.46
9	9.050	9.320	1.0298	99.34
10	9.990	10.360	1.0370	98.65
AVERAGE				100.03
STD DEV				1.17



APPENDIX G

BENCHMARK SAMPLE TEST SHEET

See overleaf.

Table G1: Test sheet for reduced benchmark sample

IDEAL									PRACTICAL				
Sample	Wave-form	I (kA)	Cc (uF)	I/Vs (kA/kV)	Twg (us)	Vs (kV)	Qg (mC)	Gap groups	Vs (kV)	I (kA)	I/Vs (kA/kV)	File	Comments
1	8/20 us	2	8.47	0.6862	12.35	2.9	25	1+1+1+1	3.0	2.0	0.6569	TEK1a,b,c,d	None, clipped, overshot, clipped
2	8/20 us	5	8.47	0.6862	12.35	7.3	62	2+2	7.0	4.7	0.6743	TEK2a,b	
3	8/20 us	8	8.47	0.6862	12.35	11.7	99	4	11.0	7.4	0.6764	TEK3	Clipped
4	8/20 us	11	8.47	0.6862	12.35	16.0	136	4	15.1	10.2	0.6781	TEK4	
5	8/20 us	13	8.47	0.6862	12.35	18.9	161	4	19.1	13.0	0.6806	TEK5	
6	8/20 us	14	33.93	2.6993	12.57	5.2	176	2+2	5.2	13.4	2.5769	TEK6a,b	
7	8/20 us	24	33.93	2.6993	12.57	8.9	302	2+2	8.8	23.2	2.6364	TEK7a,b	
8	8/20 us	34	33.93	2.6993	12.57	12.6	427	4	12.5	32.8	2.6240	TEK8	
9	8/20 us	44	33.93	2.6993	12.57	16.3	553	4	16.1	42.6	2.6460	TEK9	
10	8/20 us	53	33.93	2.6993	12.57	19.6	666	4	19.7	52.6	2.6701	TEK10	
46	4/70 us	0.4	8.47	0.0880	96.30	4.5	39	1+1+1+1	4.5	0.4	0.0889	TEK46a,b,c,d	Clipped, overshot, overshot, clipped
47	4/70 us	0.7	8.47	0.0880	96.30	8.0	67	2+2	8.0	0.7	0.0875	TEK47a,b	Clipped, clipped
48	4/70 us	1.0	8.47	0.0880	96.30	11.4	96	4	11.4	1.0	0.0877	TEK48	Clipped
49	4/70 us	1.3	8.47	0.0880	96.30	14.8	125	4	14.8	1.3	0.0878	-	Clipped
50	4/70 us	1.7	8.47	0.0880	96.30	19.3	164	4	19.3	1.7	0.0881	TEK50	Clipped
51	4/70 us	2	33.93	0.3525	96.26	5.7	193	2+2	5.7	2.0	0.3509	TEK51a,b	None, overshot
52	4/70 us	3	33.93	0.3525	96.26	8.5	289	2+2	8.5	3.0	0.3529	TEK52a,b	None, clipped
53	4/70 us	4	33.93	0.3525	96.26	11.3	385	4	11.3	4.0	0.3540	TEK53	?
54	4/70 us	5	33.93	0.3525	96.26	14.2	481	4	14.2	5.0	0.3521	TEK54	None
55	4/70 us	6	33.93	0.3525	96.26	17.0	578	4	17.0	6.0	0.3529	TEK55	Overshot
56	5/72 us	7	102.30	1.0305	99.27	6.9	705	2+2	6.9	7.0	1.0145	TEK56a,b	
57	5/72 us	8	102.30	1.0305	99.27	7.8	794	2+2	7.8	8.0	1.0256	TEK57a,b	
58	5/72 us	9	102.30	1.0305	99.27	8.7	893	2+2	8.7	8.9	1.0230	TEK58a,b	
59	5/72 us	10	102.30	1.0305	99.27	9.7	993	2+2	9.7	9.9	1.0206	TEK59a,b	
60	5/72 us	10.3	102.30	1.0305	99.27	10.0	1023	4	10.0	10.2	1.0200	TEK60	

APPENDIX H

GAP ETCHING MEASUREMENT DATA

See overleaf.

Table H1: Gap etching data (8/20 μs, 2.0 to 13.0 kA)

2.0 kA		1		2		3		4	
Etching 1	Dx								
	Dy			1.613	1.664	0.854			
	dx			1.306	1.432	0.849			
	dy								
	D/d	#DIV/0!	#DIV/0!	1.24	1.16	1.01	#DIV/0!	#DIV/0!	#DIV/0!
Etching 2	Dx								
	Dy					1.200			
	dx					1.134			
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	1.06	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)				1.65	1.87	1.64			
Amean (mm2)		1.72							
Std. dev. (mm2)		0.11							

4.7 kA		1		2		3		4	
Etching 1	Dx				0.425	0.577	1.260	1.616	
	Dy	2.290	2.295	2.265	2.447	2.186	1.825	0.437	
	dx	2.249	2.195	2.017	1.841	1.852	1.559	0.452	
	dy				0.342	0.530	1.195	1.434	
	D/d	1.02	1.05	1.12	1.33	1.17	1.13	1.11	#DIV/0!
Etching 2	Dx					0.377		1.018	
	Dy					0.269	0.333	1.461	
	dx					0.225	0.247	1.074	
	dy					0.265		0.697	
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	1.33	1.35	1.39	#DIV/0!
Etching Area per gap plate (mm2)		4.04	3.96	3.59	3.65	3.55	3.49	3.77	
Amean (mm2)		3.72							
Std. dev. (mm2)		0.20							

7.4 kA		1		2		3		4	
Etching 1	Dx	0.382	0.291						
	Dy	3.136	2.922	3.056	2.942	3.360	3.088	3.098	3.216
	dx	2.753	2.681	2.722	2.850	2.491	2.640	2.707	2.657
	dy	0.329	0.197						
	D/d	1.14	1.09	1.12	1.03	1.35	1.17	1.14	1.21
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		6.88	6.20	6.53	6.59	6.57	6.40	6.59	6.71
Amean (mm2)		6.56							
Std. dev. (mm2)		0.19							

10.2 kA		1		2		3		4	
Etching 1	Dx								
	Dy	3.680	3.670	3.565	3.629	3.435	3.488	3.451	3.514
	dx	3.190	3.146	3.247	3.200	2.272	2.257	3.261	3.213
	dy								
	D/d	1.15	1.17	1.10	1.13	1.51	1.55	1.06	1.09
Etching 2	Dx								
	Dy					2.310	2.220		
	dx					1.374	1.584		
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	1.68	1.40	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		9.22	9.07	9.09	9.12	8.62	8.94	8.84	8.87
Amean (mm2)		8.97							
Std. dev. (mm2)		0.18							

13.0 kA		1		2		3		4	
Etching 1	Dx								
	Dy	4.167	4.244	3.836	3.935	4.097	4.204	4.116	3.870
	dx	3.403	3.333	3.651	3.790	3.598	3.568	3.373	3.401
	dy								
	D/d	1.22	1.27	1.05	1.04	1.14	1.18	1.22	1.14
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		11.14	11.11	11.00	11.71	11.58	11.78	10.90	10.34
Amean (mm2)		11.19							
Std. dev. (mm2)		0.45							

Table H2: Gap etching data (8/20 μs, 13.4 to 52.6 kA)

13.4 kA		1		2		3		4	
Etching 1	Dx								
	Dy	3.914	4.079	4.125	3.966	3.991	3.877	3.842	3.885
	dx	3.686	3.690	3.532	3.531	3.660	3.851	3.757	3.788
	dy								
	D/d	1.06	1.11	1.17	1.12	1.09	1.01	1.02	1.03
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		11.33	11.82	11.44	11.00	11.47	11.73	11.34	11.56
Amean (mm2)		11.46							
Std. dev. (mm2)		0.24							

23.2 kA		1		2		3		4	
Etching 1	Dx								
	Dy	5.032	4.887	5.119	4.925	5.039	4.893	5.077	4.932
	dx	4.944	4.701	5.071	4.816	4.989	4.823	5.076	4.911
	dy								
	D/d	1.02	1.04	1.01	1.02	1.01	1.01	1.00	1.00
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		19.54	18.04	20.39	18.63	19.74	18.53	20.24	19.02
Amean (mm2)		19.27							
Std. dev. (mm2)		0.79							

32.8 kA		1		2		3		4	
Etching 1	Dx								
	Dy	5.780	5.633	6.002	5.546	5.596	5.794	5.582	5.588
	dx	5.489	5.522	5.705	5.372	5.558	5.774	5.413	5.424
	dy								
	D/d	1.05	1.02	1.05	1.03	1.01	1.00	1.03	1.03
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		24.92	24.43	26.89	23.40	24.43	26.28	23.73	23.80
Amean (mm2)		24.73							
Std. dev. (mm2)		1.17							

42.6 kA		1		2		3		4	
Etching 1	Dx								
	Dy	6.164	5.704	6.447	6.064	5.936	5.964	6.207	5.973
	dx	5.915	5.604	6.334	6.006	5.929	5.740	6.196	5.838
	dy								
	D/d	1.04	1.02	1.02	1.01	1.00	1.04	1.00	1.02
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		28.64	25.11	32.07	28.60	27.64	26.89	30.21	27.39
Amean (mm2)		28.32							
Std. dev. (mm2)		1.99							

52.6 kA		1		2		3		4	
Etching 1	Dx								
	Dy	5.848	6.033	5.961	6.173	6.258	6.166	6.036	5.929
	dx	5.840	5.986	5.836	6.171	6.206	6.112	5.870	5.870
	dy								
	D/d	1.00	1.01	1.02	1.00	1.01	1.01	1.03	1.01
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		26.82	28.36	27.32	29.92	30.50	29.60	27.83	27.33
Amean (mm2)		28.46							
Std. dev. (mm2)		1.29							

Table H3: Gap etching data (4/70 µs, 0.4 to 1.7 kA)

0.4 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy		0.792		0.948		0.792		0.855
	dx		0.712		0.678		0.719		0.675
	dy								
	D/d	#DIV/0!	1.11	#DIV/0!	1.40	#DIV/0!	1.10	#DIV/0!	1.27
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)			0.44		0.50		0.45		0.45
Amean (mm2)		0.46							
Std. dev. (mm2)		0.02							

0.7 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy				1.241		1.117		1.190
	dx				0.999		1.009		1.170
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	1.24	#DIV/0!	1.11	#DIV/0!	1.02
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)					0.97		0.89		1.09
Amean (mm2)		0.98							
Std. dev. (mm2)		0.09							

1.0 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy		1.455		1.166		1.325		1.620
	dx		1.410		0.988		1.110		1.278
	dy								
	D/d	#DIV/0!	1.03	#DIV/0!	1.18	#DIV/0!	1.19	#DIV/0!	1.27
Etching 2	Dx								
	Dy				0.523				
	dx				0.500				
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	1.05	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)			1.61		1.11		1.16		1.63
Amean (mm2)		1.38							
Std. dev. (mm2)		0.24							

1.3 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy		1.497		1.463		1.508		1.771
	dx		1.301		1.066		1.499		1.197
	dy								
	D/d	#DIV/0!	1.15	#DIV/0!	1.37	#DIV/0!	1.01	#DIV/0!	1.48
Etching 2	Dx								
	Dy				0.694				
	dx				0.684				
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	1.01	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)			1.53		1.60		1.78		1.66
Amean (mm2)		1.64							
Std. dev. (mm2)		0.09							

1.7 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy		1.269		1.814		1.934		2.255
	dx		1.165		1.757		1.723		1.523
	dy								
	D/d	#DIV/0!	1.09	#DIV/0!	1.03	#DIV/0!	1.12	#DIV/0!	1.48
Etching 2	Dx								
	Dy		1.474		0.403				
	dx		1.423		0.178				
	dy								
	D/d	#DIV/0!	1.04	#DIV/0!	2.26	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)			2.81		2.56		2.62		2.70
Amean (mm2)		2.67							
Std. dev. (mm2)		0.09							

Table H4: Gap etching data (4/70 µs, 2.0 to 6.0 kA)

2.0 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy		2.050		1.983		1.960		1.813
	dx		1.676		1.909		1.675		1.466
	dy								
	D/d	#DIV/0!	1.22	#DIV/0!	1.04	#DIV/0!	1.17	#DIV/0!	1.24
Etching 2	Dx								
	Dy		0.673						0.676
	dx		0.512						0.411
	dy								
	D/d	#DIV/0!	1.31	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	1.64
Etching Area per gap plate (mm2)			2.97		2.97		2.58		2.31
Amean (mm2)		2.71							
Std. dev. (mm2)		0.28							

3.0 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy		2.985		2.940		2.829		2.473
	dx		2.091		1.900		2.380		2.081
	dy								
	D/d	#DIV/0!	1.43	#DIV/0!	1.55	#DIV/0!	1.19	#DIV/0!	1.19
Etching 2	Dx								
	Dy								1.437
	dx								1.156
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	1.24
Etching Area per gap plate (mm2)			4.90		4.39		5.29		5.35
Amean (mm2)		4.98							
Std. dev. (mm2)		0.38							

4.0 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy		3.008		2.612		3.153		3.372
	dx		2.995		2.151		3.003		2.757
	dy								
	D/d	#DIV/0!	1.00	#DIV/0!	1.21	#DIV/0!	1.05	#DIV/0!	1.22
Etching 2	Dx								
	Dy				1.305				
	dx				0.771				
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	1.69	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching 3	Dx								
	Dy				1.239				
	dx				0.955				
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	1.30	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)			7.08		6.13		7.44		7.30
Amean (mm2)		6.99							
Std. dev. (mm2)		0.51							

5.0 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy		3.437		3.754		3.335		3.510
	dx		3.084		2.911		3.033		3.122
	dy								
	D/d	#DIV/0!	1.11	#DIV/0!	1.29	#DIV/0!	1.10	#DIV/0!	1.12
Etching 2	Dx								
	Dy		1.032						
	dx		0.909						
	dy								
	D/d	#DIV/0!	1.14	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)			9.06		8.58		7.94		8.61
Amean (mm2)		8.55							
Std. dev. (mm2)		0.40							

6.0 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy	3.801	3.949		3.726	3.798	3.919	3.732	3.748
	dx	2.954	2.967		3.676	3.132	3.303	3.171	3.199
	dy								
	D/d	1.29	1.33	#DIV/0!	1.01	1.21	1.19	1.18	1.17
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		8.82	9.20		10.76	9.34	10.17	9.29	9.42
Amean (mm2)		9.57							
Std. dev. (mm2)		0.61							

Table H5: Gap etching data (5/72 μs, 7.0 to 10.2 kA)

7.0 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy	4.181	4.061	3.929	4.131	4.228	4.237	4.009	4.080
	dx	3.956	3.997	3.876	3.859	3.479	3.731	3.847	3.928
	dy								
	D/d	1.06	1.02	1.01	1.07	1.22	1.14	1.04	1.04
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		12.99	12.75	11.96	12.52	11.55	12.42	12.11	12.59
Amean (mm2)		12.36							
Std. dev. (mm2)		0.43							

8.0 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy	4.479	4.306	4.201	4.175	4.307	4.201	4.223	4.082
	dx	3.994	3.871	4.009	3.937	3.898	3.957	4.067	4.073
	dy								
	D/d	1.12	1.11	1.05	1.06	1.10	1.06	1.04	1.00
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		14.05	13.09	13.23	12.91	13.19	13.06	13.49	13.06
Amean (mm2)		13.26							
Std. dev. (mm2)		0.34							

8.9 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy	4.706	4.411	4.438	4.403	4.556	4.340	4.486	4.257
	dx	4.571	4.163	4.440	4.226	4.259	4.173	4.450	4.223
	dy								
	D/d	1.03	1.06	1.00	1.04	1.07	1.04	1.01	1.01
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		16.89	14.42	15.48	14.61	15.24	14.22	15.68	14.12
Amean (mm2)		15.08							
Std. dev. (mm2)		0.88							

9.9 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy	4.705	4.563	4.816	4.661	4.935	4.844	4.996	4.756
	dx	4.633	4.449	4.735	4.553	4.875	4.586	4.840	4.712
	dy								
	D/d	1.02	1.03	1.02	1.02	1.01	1.06	1.03	1.01
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		17.12	15.94	17.91	16.67	18.90	17.45	18.99	17.60
Amean (mm2)		17.57							
Std. dev. (mm2)		0.97							

10.2 kA		1		2		3		4	
		-	+	-	+	-	+	-	+
Etching 1	Dx								
	Dy	5.079	4.896	4.961	4.688	5.113	4.655	5.309	4.715
	dx	4.846	4.680	4.823	4.462	4.966	4.431	5.197	4.638
	dy								
	D/d	1.05	1.05	1.03	1.05	1.03	1.05	1.02	1.02
Etching 2	Dx								
	Dy								
	dx								
	dy								
	D/d	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Etching Area per gap plate (mm2)		19.33	18.00	18.79	16.43	19.94	16.20	21.67	17.18
Amean (mm2)		18.44							
Std. dev. (mm2)		1.75							

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