August 27, 2001

Tesla Coilers:

As promised, I have attached a copy of the slides and lecture notes that I presented on August 25th, 2001 to a group of tesla coil enthusiasts. The lecture notes are a bit cryptic but show all the equations I discussed. The key ones are boxed and are on page 3 of the notes. The slides show the results of some primary circuit loss measurements I have begun taking. They indicate that the dominant loss in the primary is the spark gap if a good pulse type capacitor is used along with good wiring practices. Peak currents are in the 250-400 ampere range for even fairly small tesla coils and can easily exceed 1000 amps in a large coil system.

During the firing of the two large coils on the 25th, I measured the secondary coil peak current of each with one of my Pearson wideband current transformer. Both coils were producing twelve foot sparks to a grounded target at the time of the measurements. The conventional two coil system measured 32 amperes peak secondary current with 240 volts at 60 amperes going into the pole pig. The magnifier configuration produced 27 amperes peak current with 240 volts at 45 amperes going into the pole pig. The magnifier coil is a more efficient coil system in this case, but should not be generalized since the two coil system may not have had optimal coupling. In addition, the conventional coil system used a conventional asynchronous rotary spark gap and was observed to quench on the second notch. The magnifier system used an asynchronous multiple series rotary gap and was observed to quench on the first notch, based on observations of the secondary waveforms. Simple math indicates that the peak primary current is in the vicinity of 700-1400 amperes. I was not able to measure the peak primary current directly with this sensor. However, secondary currents in the 30 ampere range indicate the need for a fairly low gauge wire in these big coil systems. I think these secondaries are wound with 8 or 10 AWG wire. They get warm (around 90-100 degrees F) after a nice long run of 4-5 minutes.

We also did some simple tests of Marc Metlicka's novel triggered spark gap using the apparatus I am using to test primary circuit losses. The unit performed excellently! We compared the triggered gap to a single pair of tungsten electrodes operated with a spacing of 0.15" and 0.20". The triggered gap was set to the breakdown voltage used by the conventional gap and then triggering was enabled to take the measurements.

Here is the data for one and all to digest:

Spark Gap	**Breakdown Voltage**	**Peak Primary Current (Amperes)**	**# Cycles in Decrement**	**Decrement Factor**	**Quality Factor**	**R (Ohms)**
single 3/8" tungsten gap with 0.15" spacing (pair of Miller contact points)	12.6 kV	320	30	.153	20.5	1.98
single 3/8" tungsten gap with 0.20" spacing (pair of Miller contact points)	17.6 kV	410	34	.135	23.3	1.75
Marc Metlicka's triggered spark gap, total gap spacing 7/8", with center terminal 3/8" from one terminal.	12.6 kV (breakdown only occurs when triggered)	300	15	.307	10.3	3.98
Marc Metlicka's triggered spark gap, total gap spacing 7/8", with center terminal 3/8" from one terminal.	17.6 kV (breakdown only occurs when triggered)	340	19	.242	13.0	3.14

Notes:

1. Marc Metlicka's gap would not fire at 22 kV (maximum available using my D.C. power supply) when the triggering was turned off. This was not surprising since the gap spacing was 7/8".
2. Gap resistance would drop further if the voltage was raised due to the negative resistance properties of spark gaps.
3. The decrement appearance was linear, demonstrating that most of the losses were in the spark gap rather than in the connections, despite some rather poor connections in Marc's gap.
4. The noise from the gap was substantial when it fired. The ignition coil would send multiple sparks individually to each electrode, and the gap wouldn't fire until there were enough ions on both sides of the center pin, due to the rather low operating voltage compared to the gap width.
5. Operation of a triggered gap at higher voltages than this would be desirable.
6.

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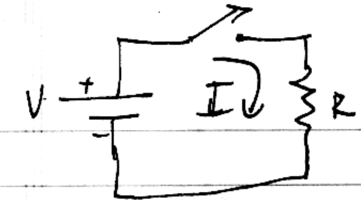
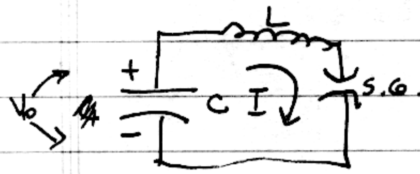
1.



$V = IR$ $\qquad I = V/R$

OHM'S LAW



$V = IZ$ $\qquad I = \frac{V}{Z}$

$Z = \sqrt{L/C} + R_{LOSSES}$

↑ SURGE IMPEDANCE

IF R_{LOSSES} IS SMALL: $V = I\sqrt{\frac{L}{C}}$ $\qquad I = V\sqrt{\frac{C}{L}}$

$(\sqrt{L/C} > 10 \times R_{LOSS}$

SOLUTION:

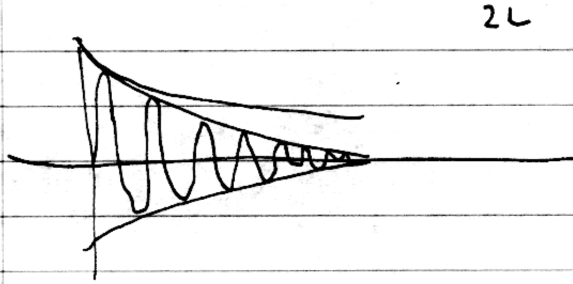
$$I = \omega C V_0 e^{-\alpha t} \sin \omega t$$

$$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \approx \frac{1}{\sqrt{LC}}$$

THIS TERM IS < 1%, IF Q > 4

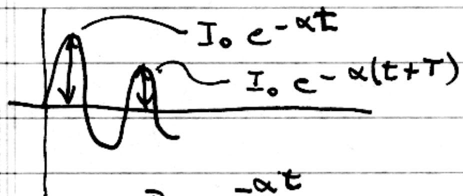
SO $I = V_0 \sqrt{\frac{C}{L}} e^{-\alpha t} \sin \frac{t}{\sqrt{LC}}$

α = DAMPING FACTOR = $\frac{R}{2L}$ = LOSSES IN CIRCUIT



2. CONSTRAINTS:

1. MINIMIZE α BY USING LARGE L OR SMALL R
2. CURRENT $\propto \sqrt{C/L}$: MAY WANT TO REDUCE TO KEEP I^2R LOSSES SMALL.
3. $V_s = V_p \sqrt{L_s/L_p}$ OR $V_s = V_p \sqrt{\frac{C_p}{C_s}}$



WHERE $T = \frac{1}{f} = \frac{2\pi}{\omega}$

$$\frac{I_0 e^{-\alpha t}}{I_0 e^{-\alpha(t+T)}} = e^{\alpha T} = e^{\frac{2\pi\alpha}{\omega}}$$

$$\text{LOG DECREMENT} = \log_e\left(e^{\frac{2\pi\alpha}{\omega}}\right) = \frac{2\pi\alpha}{\omega}$$

$\delta = \frac{\pi R}{\omega L}$ SINCE $\alpha = \frac{R}{2L}$

δ IS ALSO EQUAL TO $\frac{\pi}{Q}$ AND $\pi R \omega C = \frac{\pi R}{\sqrt{L/C}}$

δ IS:
1. A RATIO OF CURRENT AMPLITUDES
2. " " " IMPEDANCES
3. PROPORTIONAL TO $1/Q$

Q = QUALITY FACTOR = $\frac{\text{ENERGY STORED}}{\text{ENERGY DISSIPATED}}$

WANT SMALL δ (LARGE Q) SO PRIMARY LOSSES ARE SMALL

3. THE NUMBER OF OSCILLATIONS IS $\frac{4.6 + \delta}{\delta}$

IF δ IS SMALL (TYPICALLY < 0.4)

KEY → $\boxed{\delta \approx \frac{4.6}{\#\ \text{OSCILLATIONS}}}$ SO $\boxed{R_{LOSS} = \frac{\delta}{\pi}\sqrt{L/C}}$ & $\boxed{Q = \frac{\pi}{\delta}}$

∴ COUNT THE NUMBER OF OSCILLATIONS TO DETERMINE δ AND Q AND R LOSS!

$$R = R_{GAP} + R_{PRI} + R_{DIELECTRIC} + R_{RADIATION} + R_{SEC}$$

R_{GAP} IN AIR $\approx \frac{0.8 \times 10^{-3}\, dp}{C\, V}$ OHMS

d = GAP DISTANCE IN CM

p = PRESSURE IN ATMOSPHERES

C = FARADS

V = VOLTS

R_{GAP} IS INSTANTANEOUS VALUE. IT RISES AS V FALLS OR AS ION RECOMBINATION OCCURS.

→ IF THE OBSERVED DECREMENT IS LINEAR, MOST OF THE LOSSES ARE DUE TO THE SPARK GAP. LOOK AT THE WAVE FORM!

→ MEASURE R_{PRI} & Q FROM COUNTING THE NUMBER OF CYCLES!

Primary Coil Resistive Losses

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Objectives

- Describe the behavior of a damped oscillator.
- Review the concept of log decrement measurement and demonstrate how to apply it to a tesla coil primary circuit.
- Illustrate these concepts through real-world experiments.

Experiment # 1

- Objective: Determine total primary coil resistance as the distance between spark gap electrodes is varied.
- Gap: single pair of 3/8” tungsten electrodes (Miller contact points in aluminum holder).
- Capacitor: Maxwell 29.7 nF 45 kV pulse
- Coil: 14 turn solenoid, 49.1 uH, 10 AWG 9” diameter, 4.5” height, Rdc=0.35 ohms.

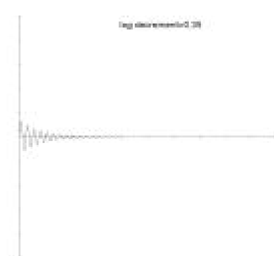
Experiment # 1

- Sensor: Pearson Model 410 wide-band 20 MHz current transformer, 0.1 volts/ampere sensitivity, .
- Resonant frequency: 132 kHz
- No secondary coil was placed in the circuit.
- Primary wire rated at 55 amperes continuous in air.

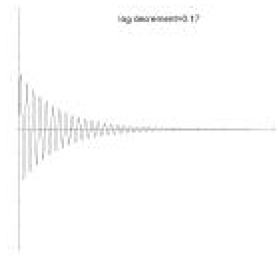
Experiment # 1

- Power supply: 0-20 kV variable D.C. supply rated at 1 kW (voltage doubler circuit, filter capacitors are 0.1 uF at 90 kV, with 100 megohm bleeder resistors).
- Decoupling: power is supplied through 3 megohm resistors on each side of the circuit (6 megohms total isolation between the power supply and the primary circuit).

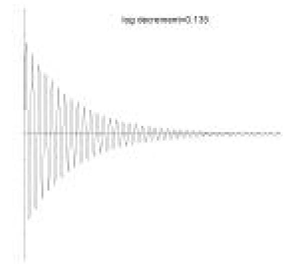
Current Versus Time Gap Spacing = 0.020 Inches Vbreakdown = 2.7 kilovolts



Current Versus Time
Gap Spacing = 0.100 Inches
Vbreakdown = 9.6 kilovolts



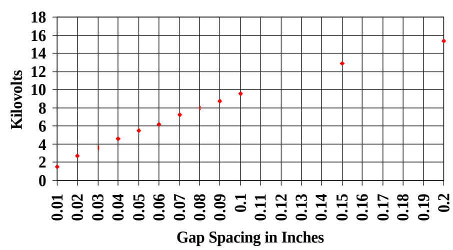
Current Versus Time
Gap Spacing = 0.200 Inches
Vbreakdown = 15.4 kilovolts



Gap Breakdown Voltage

- The voltage at which the gap breaks down is highly dependent on geometry.
- Pointed gaps break down at lower voltages than flat contacts.
- Tables are available for spherical gap geometries.
- Two flat 3/8” tungsten gaps are used here.

Gap Breakdown Voltage Versus Gap Spacing



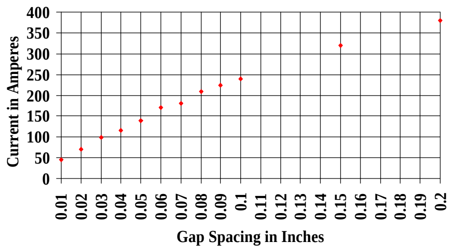
Peak Primary Current

- The peak current is directly proportional to the gap breakdown voltage.
- The peak current is also directly proportional to the square root of C/L.
- High C primary systems have huge circulating primary currents.
- 10 AWG solid copper wire is used here (rated at 55 amps continuous duty in air).

Peak Primary Current

- The surge impedance is equal to the square root of L/C.
- Ohm’s law says that V = I x R so the current is V / R.
- The maximum possible current is then V times the square root of C / L.
- Higher L/C ratios decrease primary currents.

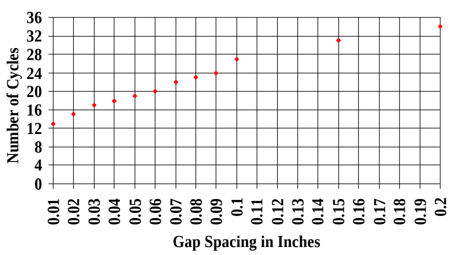
Peak Primary Current Versus Gap Spacing



Number of Oscillation Cycles

- A primary coil system with large resistive losses will damp out quickly with few oscillation cycles.
- A low loss primary system will ring down over many cycles.

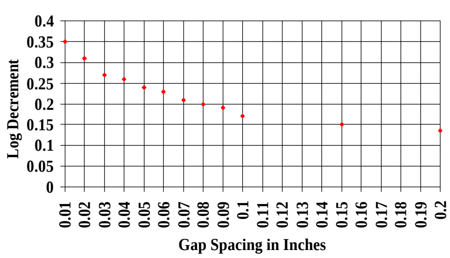
Number of Damped Oscillation Cycles Versus Gap Spacing



Log Decrement

- Decrement is a measure of the damping of the system.
- A high decrement factor is an indication of a lossy primary coil system.
- Typical decrement factors for the old spark gap transmitters were between 0.09 and 0.20.

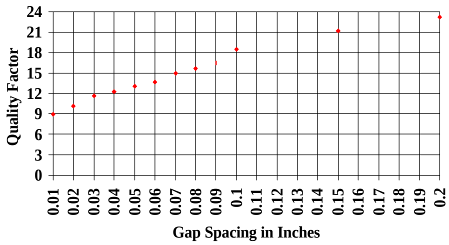
Log Decrement Versus Gap Spacing



Primary Q

- Q is the quality factor for the coil system.
- Q is the energy stored divided by the energy dissipated in the coil/capacitor system.
- A high Q factor is a sign of low losses.
- The Q of the primary should be matched to the Q of the secondary for maximum power ttransfer.

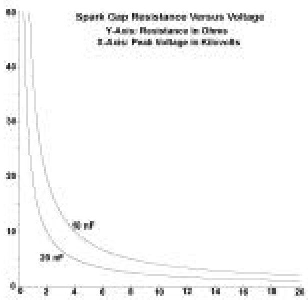
Unloaded Primary Q Versus Gap Spacing



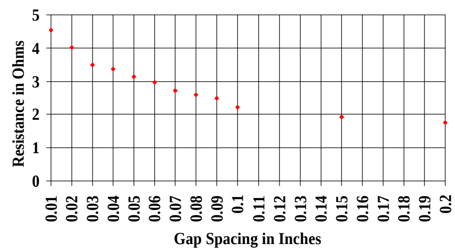
Total Resistance

- The total primary system resistance can be determined from the decrement factor.
- Gap resistance decreases as the primary current increases.
- Lossy capacitors or poor connections may greatly increase the total resistance.
- The contribution of each cannot be distinguished in this experiment.

Toepler's Formula



Total Resistance Versus Gap Spacing



Total Resistance

- The addition of a coupled secondary coil operating at resonance behaves as if an additional series resistance were added to the primary circuit.

Experiment # 2

- Objective: Determine total resistance as the capacitor is varied.
- Gap: single pair of 3/8" tungsten electrodes (Miller contact points in aluminum holder). Measure system parameters using 0.05", 0.010" and 0.015" gap spacings.
- Coil: 14 turn solenoid, 49.1 uH, 10 AWG 9" diameter, 4.5" height, Rdc=0.35 ohms.

Experiment # 2

- Sensor: Pearson Model 410 wide-band 20 MHz current transformer, 0.1 volts/ampere sensitivity, .
- Resonant frequency: 91-406 kHz, depending on the capacitor used.
- No secondary coil was placed in the circuit.
- Primary wire rated at 55 amperes continuous in air.

Experiment # 2

- Power supply: 0-20 kV variable D.C. supply rated at 1 kW (voltage doubler circuit, filter capacitors are 0.1 uF at 90 kV, with 100 megohm bleeder resistors).
- Decoupling: power is supplied through 3 megohm resistors on each side of the circuit (6 megohms total isolation between the power supply and the primary circuit).

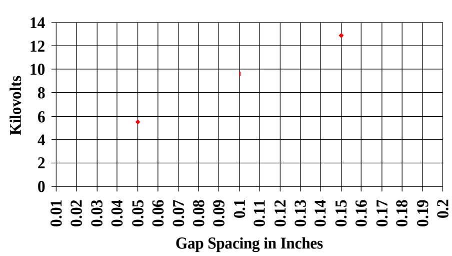
Experiment # 2

- Nine different capacitors were used in this study.
- They vary in capacitance from 3.1 nF to 61.9 nF.
- They are labelled A-I on the graphs and are identified on a later slide.

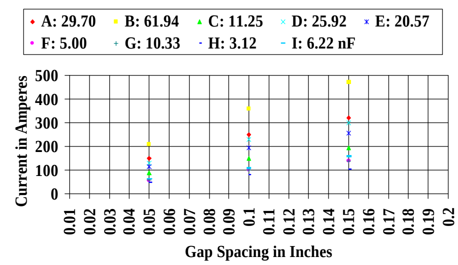
Experiment #2 - Capacitors

- A - Maxwell pulse type, 29.70 nF
- B - Maxwell pulse type, 61.94 nF
- C - Maxwell pulse type, 11.25 nF
- D - Condenser Products pulse type, 25.92 nF
- E - Plastic Capacitors mylar OFN series, 20.57 nF
- F - Plastic Capacitors pulse type, BNZ series, 5.00 nF
- G - Plastic Capacitors paper LN series, 10.33 nF
- H - Panasonic 1 x 18 x 56 nF Panasonic MMC, 3.12 nF
- I - Panasonic 2 x 18 x 56 nF Panasonic MMC, 6.22 nF

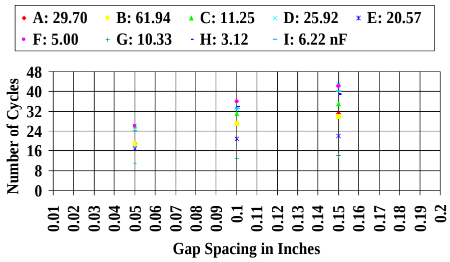
Gap Breakdown Voltage Versus Gap Spacing



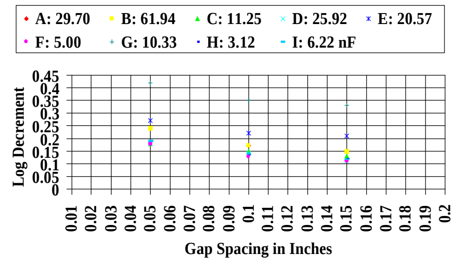
Peak Primary Current Versus Gap Spacing



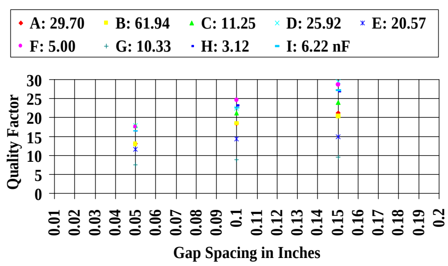
Number of Damped Oscillation Cycles Versus Gap Spacing



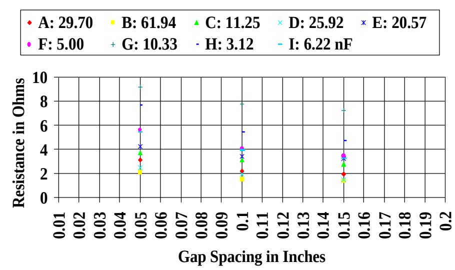
Log Decrement Versus Gap Spacing



Unloaded Primary Q Versus Gap Spacing



Total Resistance Versus Gap Spacing



Total Resistance in Ohms for a Gap Spacing of 0.10”

- 2.20 A - Maxwell pulse type, 29.70 nF
- 1.53 B - Maxwell pulse type, 61.94 nF
- 3.12 C - Maxwell pulse type, 11.25 nF
- 1.93 D - Condenser Products pulse type, 25.92 nF
- 3.41 E - Plastic Capacitors mylar OFN series, 20.57 nF
- 4.03 F - Plastic Capacitors pulse, BNZ series, 5.00 nF
- 7.77 G - Plastic Capacitors paper LN series, 10.33 nF
- 5.40 H - Panasonic 1x18x56 nF Panasonic MMC, 3.12 nF
- 3.94 I - Panasonic 2x18x56 nF Panasonic MMC, 6.22 nF

Figure of Merit - (Small is Good) = Total Resistance / Sqrt (C)

- .40 A - Maxwell pulse type, 29.70 nF
- .19 B - Maxwell pulse type, 61.94 nF
- .93 C - Maxwell pulse type, 11.25 nF
- .38 D - Condenser Products pulse type, 25.92 nF
- .75 E - Plastic Capacitors mylar OFN series, 20.57 nF
- 1.80 F - Plastic Capacitors pulse, BNZ series, 5.00 nF
- 2.42 G - Plastic Capacitors paper LN series, 10.33 nF
- 3.06 H - Panasonic 1x18x56 nF Panasonic MMC, 3.12 nF
- 1.58 I - Panasonic 2x18x56 nF Panasonic MMC, 6.22 nF

Experiment # 3

- Objective: Compare resistance of single versus multiple gap systems.
- Capacitor: Maxwell 29.7 nF 45 kV pulse
- Coil: 14 turn solenoid, 49.1 uH, 10 AWG 9” diameter, 4.5” height, Rdc=0.35 ohms.

Experiment # 3

- Sensor: Pearson Model 410 wide-band 20 MHz current transformer, 0.1 volts/ampere sensitivity, .
- Resonant frequency: 132 kHz
- No secondary coil was placed in the circuit.
- Primary wire rated at 55 amperes continuous in air.

Experiment # 3

- Power supply: 0-20 kV variable D.C. supply rated at 1 kW (voltage doubler circuit, filter capacitors are 0.1 uF at 90 kV, with 100 megohm bleeder resistors).
- Decoupling: power is supplied through 3 megohm resistors on each side of the circuit (6 megohms total isolation between the power supply and the primary circuit).

Experiment # 3

- Gap #1: single pair of 3/8” tungsten electrodes 0.10”.
- Gap #2: series pair of 3/8” tungsten electrodes with equal spacing 0.05” each.
- Gap #3: 10 series gaps with .010” spacing each.
- Gap #4: 10 series gaps with .015” spacing each.

Experiment # 3 Results

#1	V= 9.6 kV	I=249 A,	Q=18.4	R=3.21
#2	V= 9.9 kV	I=255 A,	Q=12.3	R=3.31
#3	V= 7.5 kV	I=175 A,	Q= 4.1	R=9.94
#4	V=12.9 kV	I=310 A,	Q= 7.5	R=5.42

Conclusions

- Typical primary circuit Q = 10-20.
- Resistive gap losses dominate and depend on primary circuit peak current and have a negative resistance characteristic.
- Typical gap resistance: 1-5 ohms
- Peak primary currents may exceed 1000 amperes in large coil systems.

Conclusions

- Large gap spacings reduce gap losses significantly since Vbreakdown is increased and Rgap is reduced.
- Single gaps appear to work better than multiple gaps in single-shot mode (but may not quench as well).
- Perhaps a triggered gap does have a use after all!

For More Information

- Contact Mark Rzeszotarski via E-mail: msr7@po.cwru.edu