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(Excerpt from Quarterly Report for March, April, May, 1952 - Linac Group - UCRL-1903)

M. Kilpatrick
August, 1952

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Berkeley, California
SPARKING AND X-RAYS IN A MERCURY PUMPED VACUUM SYSTEM

W. Kilpatrick

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Sparking: The most obvious conclusion about 200 m.c. sparking is that it follows strictly surface gradient\(^1\) and does not depend upon total voltage. In order to arrive at this conclusion, a quantitative means for measuring the probability of sparking had to be constructed, since it was clearly evident that the d.c. notion of sparking was inadequate. Counting equipment previously described\(^2\) was used to establish that at constant gradient

\[
\frac{dn}{dt} = n^{-K_1}, \quad K_1 > 0
\]

where \(K_1\) is a constant, \(n\) is the number of sparks accumulated prior to time \(t\), and \(dn/dt\) is the sparking rate. When sparks occurred using copper electrodes, there was no exception to equation (1) for all surface gradients up to 0.82 MV/cm, where \(3.3'' < \text{gap} < 8.75''\). Higher gradients were not available due to r.f. power limitation. When \(dn/dt\) decreased a few orders to one spark in fifteen minutes, the corresponding \(n\) was defined at \(N\). \(N\) was then interpreted to be the inherent number of sparks required before sparking ceased to exist at that gradient. It was then

\(^1\)Surface gradients were measured by A. Schelberg, using the BB technique.

\(^2\)W. Kilpatrick, UCRL-1573, 5, (1951).
found, by using various surface and gap geometries, that \( N \) could be calculated for copper on a gradient basis for \( N = 10,000 \), using the expression,

\[
N = \left( \frac{E}{E_0} \right)^2 e^{\alpha \left( 1 - \frac{E_0}{E} \right)}, \quad \alpha = 4.9
\]  

(2)

where \( E \) is surface gradient in MV/cm, \( E_0 \) is defined as the threshold or surface gradient at which sparking first occurs. If \( E \) varies over an electrode surface, equation (2) takes the form,

\[
N = \frac{1}{A_0} \left( \frac{E}{E_0} \right)^2 e^{\alpha \left( 1 - \frac{E_0}{E} \right)} \frac{dA}{dA}, \quad \alpha = 4.9
\]  

(3)

where \( A_0 \) is the area affected by \( E_0 \) for sparking, and the limits for integration are governed by the extent of \( E \geq E_0 \). The agreement of the calculated \( N \) with measured \( N \) is shown in Fig. 1. Four of various copper geometries used for field configuration were:

<table>
<thead>
<tr>
<th>Case</th>
<th>Surface</th>
<th>Maximum Surface Curvature</th>
<th>Electrode Diameter</th>
<th>Gap</th>
<th>Maximum Recorded ( E_n )</th>
<th>Maximum Recorded ( V )</th>
<th>( E_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Elliptical</td>
<td>7.5&quot;</td>
<td>8.75&quot;</td>
<td>0.20</td>
<td>2.75</td>
<td>0.097</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Stove-pipe</td>
<td>0.021&quot;</td>
<td>5.5&quot;</td>
<td>0.37</td>
<td>2.1</td>
<td>0.068</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Hemisphere</td>
<td>0.500&quot;</td>
<td>1.0&quot;</td>
<td>0.82</td>
<td>2.45</td>
<td>0.187</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Stove-pipe</td>
<td>0.031&quot;</td>
<td>1.0&quot;</td>
<td>0.53</td>
<td>1.7</td>
<td>0.119</td>
<td></td>
</tr>
</tbody>
</table>

where \( E \) and \( E_0 \) are in MV/cm, and \( V \) is in kV. It should be emphasized that \( E_0 \) in all cases was made as high as possible by careful cleaning, phosphoric acid deplating, and avoiding dust. To establish equation (1) as dependent only on the number of accumulated sparks, an overvoltage technique was used. At constant gradient, the sparking rate was allowed

\[ This \ procedure \ was \ previously \ used \ to \ reduce \ sparking, \ W. \ Kilpatrick, \ UCRL-1573, \ 5 \ (1951). \]
to diminish; the gradient was increased in order to spark more rapidly; then the gradient was decreased to the original value. The subsequent sparking rate was predicted precisely by Eq. (1).

Expressing Eq. (1) in terms of time predicts that

\[ \frac{du}{dt} \sim t^{-1} \]  

(4)

This relation was verified experimentally, as far as the statistics of low sparking rates would allow.

Since sparking was gradient dependent, and since very high x-ray intensities (presumably electronic in origin) accompanied the sparking, it was not surprising to find that the charge transport for discharging the majority of stored energy was electronic.\(^4\) To infer this, x-ray intensity was calibrated against an auxiliary electron current directed across the gap, and the amplitude of the x-ray bursts during a spark was measured. The data indicated that electronic transport was sufficient for discharge of the stored energy. The gap at the time of these measurements was 3.3\(\text{\textmu} \text{m} \); the gap voltage was 1.5 MV; and two r.f. cycles were apparently the main time-component of the x-ray bursts during a spark.

X-Rays: A correlation (apparently independent of voltage or gradient) between x-ray background and initial sparking rate was previously reported.\(^5\) In addition, it has been found that minimum measurable x-ray intensities (about 0.5 mr/hr) occur at the sparking threshold, \(E_0\). X-ray background intensity at constant voltage seems to require the same relation as sparking at constant voltage, namely

\(^4\)C. S. Munan, UCRL-1573, 12 (1951).

\(^5\)W. Kilpatrick, UCRL-1680, 7, (1951).
\[
\frac{dR}{dt} = R^{-a}K_2, \quad K_2 > 0 \\
a \equiv 1
\]  

where \(K_2\) is a constant, \(R\) is the accumulated roentgens, and \(dR/dt\) is the rate. \(K_2\) for x-rays was less than \(K_1\) for sparking (order of 1:1000). Moderate heating of the electrodes (r.f. heating for example) apparently affects Eq. (5) slightly. The effect was not measured, but a suggested modification is that \(a = 1 + f(T)\), where \(T\) is the electrode temperature.

At this stage in the experiments, it appeared that x-rays and sparking were similar phenomena — differing only in magnitude of electronic charge transport. At present, it is felt that no contradictory evidence to this statement has been obtained.

Experimental Results: Various metals were used for electrodes. Each metal indicated a finite number of inherent sparks. For comparison only, the approximate results are summarized here in order, for samples having the same gradient on a one inch diameter hemispherical surface:

<table>
<thead>
<tr>
<th>Material</th>
<th>(E_0)</th>
<th>Inherent Sparske</th>
<th>Initial Spark Rate</th>
<th>Initial X-ray Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rh</td>
<td>0.39</td>
<td>400</td>
<td>151</td>
<td>0.02</td>
</tr>
<tr>
<td>Cu(CFHC)</td>
<td>0.27</td>
<td>250</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>Cu</td>
<td>0.18</td>
<td>1250</td>
<td>350</td>
<td>2.0</td>
</tr>
<tr>
<td>Au</td>
<td>0.23</td>
<td>1300</td>
<td>134</td>
<td>3.0</td>
</tr>
<tr>
<td>Cr</td>
<td>0.25</td>
<td>1600</td>
<td>127</td>
<td>0.5</td>
</tr>
<tr>
<td>Mo</td>
<td>0.25</td>
<td>2300</td>
<td>306</td>
<td>14.0</td>
</tr>
<tr>
<td>Invar</td>
<td>&lt;0.20</td>
<td>2900</td>
<td>-</td>
<td>4.0</td>
</tr>
<tr>
<td>Cu-0</td>
<td>0.26</td>
<td>&gt;2000</td>
<td>&gt;80</td>
<td>0.8</td>
</tr>
<tr>
<td>Al</td>
<td>0.20</td>
<td>56000</td>
<td>455</td>
<td>2.0</td>
</tr>
<tr>
<td>Sn</td>
<td>0.25</td>
<td>80000</td>
<td>121</td>
<td>1.5</td>
</tr>
<tr>
<td>Graphite</td>
<td>0.08</td>
<td>10000x</td>
<td>&gt;5000x</td>
<td>20.0x</td>
</tr>
</tbody>
</table>

where the voltage for x-ray and spark data listed was 2.3 MV across a gap of 3.3" for all cases except graphite. The voltage for graphite*
was 1.0 MV and could not be increased, apparently due to extreme "electron loading". Rhodium seemed to be the most desirable metal for few sparks and low x-ray background. The sample listed above was a plating of about \(0.1 \times 10^{-3}\) inches of Rh on a plating of about \(0.1 \times 10^{-3}\) inches of Ni on solid copper. It is felt that if a thicker coating of Rh could have been obtained, the inherent sparking would have been less than OFHC copper. Mo had a very high initial x-ray background which decreased fairly rapidly toward the level of copper or chromium. Mo however, was easily recontaminated by air -- just relieving the vacuum with air and then pumping down immediately sensibly returned every inherent spark that had been previously removed. Mo was the only metal used which was so completely recontaminated by air. When oxidized copper\(^6\) was used, the initial sparking rate and x-ray level was low. Increasing the voltage, however, to approximately 2.1 MV (corresponding surface gradient 0.72 MV/cm) apparently broke away parts of the oxide coating and a large increase in sparking rate ensued. Invar became cherry-red as a result of energy dissipation. Al showed clean-up tendencies above threshold sparking, but at one particular gradient, an unusually large number of sparks occurred--similar to copper oxide, just described. After the large number of sparks had been run out from one small spot, the Al behaved normally like Cu or Cr, and cleaned up. The total number of sparks in the Al was 56,000; of this total, approximately 53,000 came from the small spot. Sn behaved like Al. Carbon in the form of graphite was a

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\(^6\)Previously described. W. Kilpatrick, UCRL-1680, 7, (1951).
prolific emitter even when outgassed, but exhibited the same tendency to clean up as did the metals.

In order to include the sparking behavior of Sn and Al as well as to anticipate a similar behavior for copper, Eq. (1) should be modified in such a way that the constant $K_1$ is unaffected by the abnormal flurry of sparks at a critical gradient. An expression which seems to apply is:

$$\frac{du}{dt} = (n - n_0 (E, A))^{-K_1}, K_1 >> 0$$

(6)

where $n_0$ is the unusually large number of sparks (or flurry) which depend on a critical gradient and/or critical area. For all observations using copper, it should be emphasized that $n_0(E, A) = 0$ for gradients up to 0.82 MV/cm.

A "damage" experiment was conducted using Sn-coated electrodes (M.P. of Sn is 231°C). The geometry of these electrodes was assymmetric—a blunt point facing a nearly plane surface. It was demonstrated that the electron emitting surface was damaged during the actual spark, and that no visible damage occurred to the electron bombarded side. To clarify the geometry, the electron emission came from the point, the x-rays came from the plane, and the point was damaged.

A spectrographic analysis of the "cathode" light associated with a spark was attempted. A very sharp, pointed copper electrode was observed through the bore of a stove-pipe electrode. The approximate condition for sparking was: surface curvature 0.1 mm, 0.4 MV, 4° gap, surface gradient 20 MV/cm. The results of this experiment were not
considered useful in interpreting normal sparking. However, four clear observations were made: Spectral analysis of "cathode" light is possible; copper spectra was present and originated at, or very near, the point electrode; glow-discharge using air presented a molecular spectrum; the "cathode" light was probably associated with electron emission effects and not with ions crossing the entire gap. The argument for ions not crossing the entire gap is based on divergent field near the point, transit time for ions, and the fact that visible light was restricted to a very small region about the point.

Spark Mechanism: The general problem concerning r.f. and d.c. sparking is to obtain a minimum sparking rate. In order to accomplish this, an exact knowledge of the initiation mechanism seems required, and events which are subsequent to initiation should be relatively unimportant.

Events leading up to and including the major charge transport and considered here as spark initiating. There seems to be an advantage in using r.f. for such an investigation because ion transit time is a small contributing factor. It is felt that there is much information, both r.f. and d.c., which could be used to construct an adequate initiation mechanism, but that it is not sufficient at present. The following facts are intended to clarify the important points concerning this initiation phase:

1. There is a definite threshold gradient \( E_0 \) for sparking a given metal in a practical vacuum system.

   a. D.C. - J. W. Beams, Phys. Rev. 44, 803, (1933). Using a liquid mercury cathode and stainless steel anode, the breakdown voltage was critical and could be changed slightly with the purity of the mercury.
b. 200 m.c. - First part of this report. Using a threshold hypothesis, an analysis of the sparking could be made.

2. Higher electron emission currents are produced during spark initiation than can be accounted for by field emission alone.

a. D.C. - W. P. Dyke, Field Emission Seminar Abstracts, Linfield College, Oregon, (1952). The theoretically derived relation of Fowler and Nordheim for field emission was confirmed experimentally over a wide range of gradient (up to about 300 MV/cm).

b. D.C. - J. W. Beams, Phys. Rev. 44, 803, (1933). Calculations show that sparking occurs with large electronic currents when the surface gradient will allow 1 electron/cm²/sec.


d. 200 m.c. - First part of this report. Sparking can occur at a surface gradient of less than 100 KV/cm, and large electron currents accompany the spark.

3. The major charge transport is electronic.


Electrons are emitted first and secondary effects involving ions apparently depend upon low voltage after the major electron discharge.


A fraction of the total conduction is attributable to ions, and their principle effect is to increase
electron emission at subsequent lower gradient.

c. 12 m.c. - C. S. Numan, UCRL-1573, 12, (1951). The inference was that the major charge transport for sparking was electronic. There also seems to be supporting evidence from "crowbar" experiments.

d. 200 m.c. - First part of this report. The inference is made from x-ray intensities, that the transport is electronic.

4. X-rays, sparks, and "drain" are a similar if not identical phenomena as far as initiation is concerned.

a. D.C. - W. H. Bennett, Phys. Rev. 27, 582 (1931). Observed relatively large current premature to breakdown suggesting the possibility of time distribution of "drain".


It was shown that pre-breakdown currents (drain) required the same "total voltage effect" for varying gap as previous investigation found for sparking.

c. 200 m.c. - First part of this report. Sparks and x-rays appear identical except in the magnitude of charge transport.

5. The electron emitting surface can be damaged by sparking.

a. D.C. - R. Haefer, Z. Physik 116, 604, (1940). Observations with an electron microscope indicated that for experiments in a residual gas atmosphere of argon at a pressure of about $10^{-5}$ mm, the sharpness of emitting points may be increased as pre-breakdown current flows. Haefer was able to melt these points by increased field emission currents.
b. 200 m.c. - First part of this report. Sn (MP. = 231°C) was used.

6. Ions are not required to cross the entire gap for spark initiation.
   a. D.C. - W. H. Bennett, Phys. Rev. 27, 582, (1931). Using a magnetic field it was shown that positives from the anode have questionable influence on the initial cathode emission.

b. 12 m.c. - C. S. Nunan, UCRL-1573, 12, (1951). A theoretical analysis of ion trajectories showed the impossibility for ions to migrate toward the higher field electrode.

c. 200 m.c. - First part of this report. Sparks occurred from small radius of curvature surfaces, and the theoretical ion trajectory argument of 12 m.c. holds.

7. The sparking rate at a given voltage diminishes with time and/or the number of sparks.

   a. This seems to be generally observed at all frequencies including d.c., with the provision that the vacuum system be moderately free of contamination including oil.

8. Localized gas pressure can induce sparking.

   a. D.C. - H. Heard and E. Lofgren, UCRL-1680, 22, (1952). Although an experiment was not described that specifically induced sparks, observations indicate an exponential increase in gas pressure which could be associated with "drain" and sparking.

   b. 200 m.c. - W. Kilpatrick, UCRL-1774, 9, (1952). Sparks were induced when gas was admitted through a hold (diameter = .040") in one electrode. Without regard to the kind of
gas used, a local pressure of about $10^{-1}$ mm was required.

9. Gradient and not VE is the criterion for r.f. sparking.
      This article presents literature and evidence for VE const., or the fact that a "total voltage effect" exists for d.c.
   b. 200 m.c. - First part of this report. Gradient is of prime importance, indicating that the "total voltage effect" of d.c. is secondary to initiation.
      2.0 MV was supported across a 2.0" gap, resulting in a higher VE product than would be expected from D.C. experience.

10. The work function concept is inapplicable in that "drain" or x-rays have a distribution in time, and a time average of these discontinuities does not meet the conditions for the Fowler-Nordheim type of field emission.
   a. References are similar to item 4, above.

11. Local pin-point gradients is an inadequate argument for enough primary electron field emission current to dissipate the stored energy in a spark.
a. References are similar to item 2.

12. Different base metals do not change the sparking threshold nor the subsequent sparking rate radically.

I Corollary. Cleaning before installation in the vacuum system is more noticeable than changing base metals.

II Corollary. Metallurgically or chemically pure metals decrease the sparking rate slightly as compared with commercially available metals.

13. Visible light is associated with the electron emitting surface during a spark.
   b. 200 m.c. - First part of this report. The visible light is capable of spectrographic analysis.

14. An electrostatically biased gap-splitter can change the x-ray background.
   b. 200 m.c. - W. Kilpatrick, UCRL-1680, 7, (1951). This observation is interpreted to mean that ions not crossing the gap can affect x-rays and spark initiation.

15. Spark initiation is not affected by the temperature of the electrodes up to thermionic emission.
   a. D.C. - A. J. Ahearn, Phys. Rev. 50, 238, (1936). Experiments indicate that on clean surfaces of Mo, W, and thoriated tungsten there is no field current temperature effect nor temperature effect on voltage breakdown. Also,
anode heat-conditioning in a sealed tube indicated no affect on voltage breakdown.

b. 200 m.c. - W. Kilpatrick, UCRL-1573, 5, (1951). Heating copper electrodes to about 300°C for several hours did not change the x-ray intensity background markedly.

16. Ions can be produced in the immediate neighborhood of the electron emitting surface.

a. D.C. - Trump and Van de Graaff, Journ. App. Phys. 18, 327, (1947). The evidence is not conclusive, but it may be inferred that residual gas may be ionized with about 2 KV electron energy at the rate of 9 positive ions to one electron.

b. 200 m.c. - No evidence, but strongly suspected as a phase in the construction of a local Malter layer on the cathode.

17. 12R heating occurs in the electron emitting surface due to electron emission.


b. 200 m.c. - No evidence.

18. Sparks are not spontaneous, and require a finite time for the initiation phase.

a. D.C. - Many references.

b. 10 m.c. - R. Birge, E. Lauer and E. Lofgren, UCRL-1680, 15 (1951). X-rays apparently built up in a test cavity for at least 3 cycles as a prelude to a spark.
Acknowledgements:

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