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BEHAVIOR OF SPARK GAP SWITCH IN HIGH-Q RINGING CIRCUIT

by

F.H. Tenney

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NSA

The present experimental program of the Model C Stellarator at the Princeton Plasma Physics Laboratory calls for the construction of a 240 kv -high-Q ringing circuit to be used to heat the plasma in the Stellarator. It is hoped that significant heating of the plasma will result if the Q of the ring is appreciably grater than 100.

The high-Q ringing circuit has been under development for some time. This paper will report some observations that I and my collegue John Harrison have made on the spark gap switch employed in the ringing circuit.

Experimental results with ringing circuits indicated that two gaps in series produce greater losses than a single gap, and that two gaps fired in parallel produce about the same losses as a single gap. Hence the spark gap was viewed as a constant voltage device, its polarity reversing with the current.

On the basis of this model for the behavior of a spark gap, analysis of a simple LCR circuit containing a spark gap switch leads to the result shown on the first slide. The effective Q of the ringing discharge will vary as the ring proceeds. For any particular cycle the effective Q can be defined in terms of succeeding peak voltages and is related to the passive Q of the circuit as indicated in the

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second equation. The second term on the right hand side represents the effect of the gap and can be used to define the Q of the spark gap. One notes that as the peak voltage in the ring drops, the effect of the gap on the overall Q of the circuit increases. This result is not exact, but is rather precise as long as V_g is less than 1% of V_o and $Q > 10$.

(exact result: $e^{\pi/2Q_{eff}} = e^{\pi/2Q} = \dfrac{1}{1 - V_g/V_0\,(1+e^{\pi/2Q})}$

Note that if the gap voltage is 157 volts when the peak voltage is 100 kv, the gap behaves like a circuit element having a Q of 500.

The bottom equation follows from the preceeding one and affords a simple way to display the record of the ringing discharge. By plotting on semi-log paper the peak voltage, or equivalently the peak to peak voltage of various cycles through the ring, the effective Q of the discharge for any cycle can readily be determined from the slope of the resulting curve. Thus V_o / Q_{eff} can be determined and plotted against V_o. If the model of gap behavior is adequate, a straight line should result with a slope equal to the reciprocal of the passive Q, i.e., with a slope proportional to the passive resistance of the circuit, and with an intercept on the abscissa equal to $4/\pi$ times the gap voltage.

(slide off).

The following data was obtained in the course of testing some high-Q capacitors of about 1/6 μf to 1/4 μf and rated at 60 kv. The test circuit consisted of the test capacitor, a suitable inductance to produce a ringing frequency of about 100 kc and the spark gap switch.

The second slide shows a schematic of the spark gap. The spark gap operates in air at about atmospheric pressure and consists of two stainless steel electrodes in the form of spherical caps. The minimum gap spacing is 1 1/4" and holds off about 80 kv at one atmosphere of pressure. The gap also contains four trigger electrodes made from 1/8" dia. tungsten rod. The trigger electrodes are equispaced around the center line of the spark gap and project radially to within about 3/4" of the center line.

(slide off).

The capacitor testing was an accelerated life test and discharge voltage ranged from some 40 kv to 100 kv with the bulk of the discharges being 60 kv to 80 kv range. The discharges had initial effective Q's in the vicinity of 100 so that a total of about 1 coulomb was passed by the gap in each discharge. Air was blown through the gap such that the air surrounding the gap was essentially replaced between shots. The repetition rate was about one every two or three seconds. The gap performance remained unchanged for a few hundred thousands shots after which triggering became increasingly difficult. This difficulty was a consequence of the eroding away of an inch or more in length of the trigger electrodes. Although the main electrode suffered obvious erosion proximal to each of the trigger electrodes, replacement of the trigger electrodes sufficed to restore the operating characteristics of the gap.

During the testing the capacitor voltage was monitored from time to time. In the third slide typical rings are shown. They both are typical, the top ring being what we called a "long" ring and the bottom ring being a "short" ring. In general the length of the rings varies in an erratic fashion. Although no systematic study of ring lengths has been made, the general impression is that the short rings predominate as the erosion of the trigger of electrodes becomes excessive. However, both "long" and "short" rings appeared from the start of the capacitor life testing. Since these tests ran well over 100,000 shots for each capacitor, the presence of both types of rings cannot be attributed to partial breakdown of the test capacitors.

In the fourth slide are two more rings, a "long" and an "intermediate" ring at the top. Note that the top ring displays an abrupt change in Q near the end.

The fifth slide shows the V/Q verses V plot of the rings of the previous two slides together with data of some other shots. The abscissa is incorrectly labelled and should read V over Q effective. The data from the long and short ring previously shown are the "X's" and the squares respectively. The data from the intermediate ring and long ring just show up here as the open triangles and the half closed triangles.

I direct your attention to the long ring data which lie pretty much along the lower straight line having an intersept at 175 volts. The straight line does not represent the mean of the data presented on the slide but rather the mean of a much larger number of long rings obtained in the course of testing certain of the high-Q capacitors.

This long ring data indicates that our model of gap behavior has some validity and from the data we conclude the effective gap voltage to be $\frac{\pi}{4} \times 175 = 138$ volts. From the slope of the straight line we find the passive circuit Q to be 180, which, in view of the measured Q of 240 for the test circuit exclusive of the test capacitor, leads to the conclusion that the test capacitor has a Q of something like 720 at the ringing frequency of about 100 kc.

By comparisson the upper straight line has been drawn parallel to the lower one and with an intercept of twice 175 or 350 volts. The parallel slope indicates no change in the passive circuit Q, but the intercept at 350 volts is what might be expected if the discharge in the spark gap took place in two steps, such as from main electrode to trigger electrode and thence as a separate discharge from the trigger electrode to the opposite main electrode. The spark gap would thus be acting like two spark gaps in series and since two cathode "falls" would be involved, the effective gap voltage might be expected to essentially double. To the extent that the short ring data falls along the upper straight line we feel we have evidence for the occurrance of such a double moding of the spark gap discharge.

Furthermore the double mode of gap discharge leads to an effective Q for the gap at 100 kv of 286 which is very nearly prohibitive for use in the high-Q ringing circuit envisaged for the Model C Stellarator at Princeton. Consequently the design of the spark gap is currently being reconsidered.

One final comment about the irregular data of the half closed triangles. I don't know what happened. The capacitor went through over 100,000 additional shots after this particular shot, and at higher voltages, before testing was terminated. My only comment is that I have seen data of a somewhat similar nature to the almost constant voltage portion of the plot from gaps of a quite different design where the arc seems to stretch during the course of the ring. But this is another subject.

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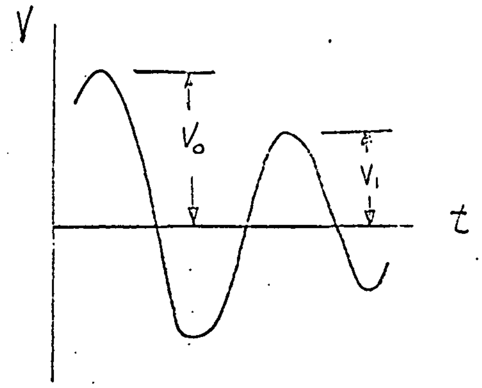
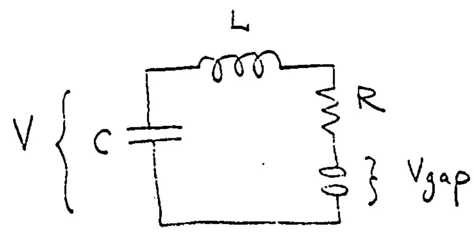




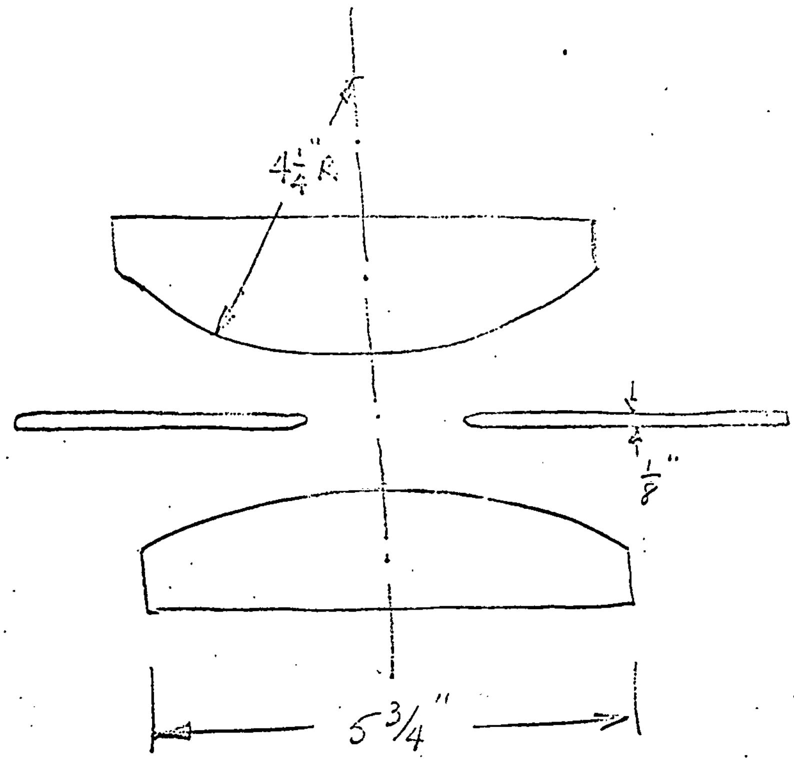
$$Q \equiv \frac{\omega L}{R} \approx \frac{1}{\omega C R}$$

$$V_1 \equiv V_0 \, e^{-\pi/Q_{eff}} \quad \cdots\cdots \text{①}$$

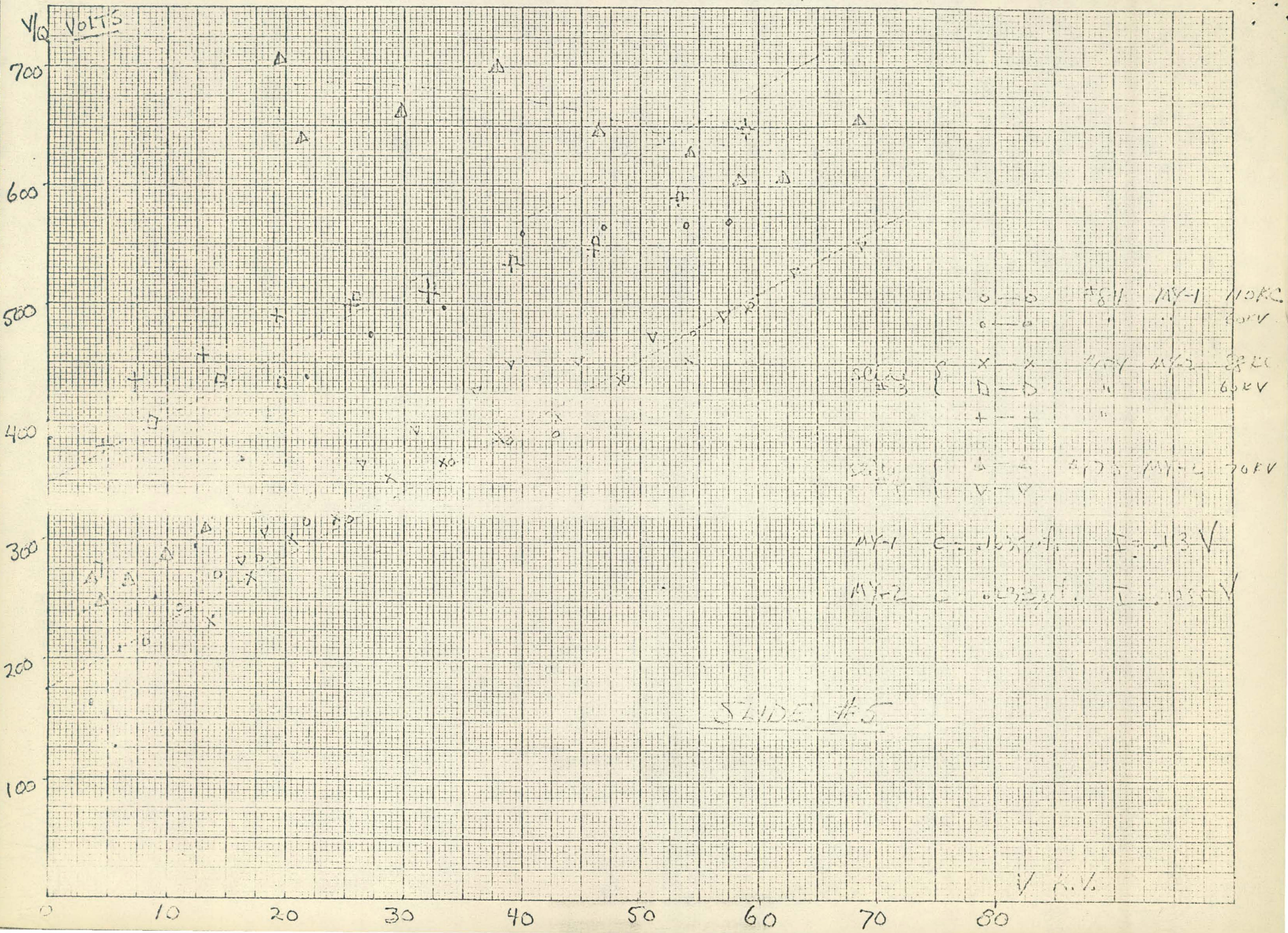
$$\frac{1}{Q_{eff}} = \frac{1}{Q} + \frac{4}{\pi}\frac{V_g}{V_0} \quad \cdots\cdots \text{②}$$

i.e. $$\frac{V_0}{Q_{eff}} = \left(\frac{1}{Q}\right) V_0 + \frac{4}{\pi} V_g \quad \cdots\cdots \text{③}$$

SLIDE # 1



SLIDE # 2


V/Q VOLTS
700
600
500
400
300
200
100
0
10
20
30
40
50
60
70
80
MY-1
110KC
65KV
70KV
MY-1
MY-2
SLIDE #5
V K.V.