Wayne Koska
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The Ringing Technique for Determining Turn to Turn Electrical Shorts in SSC Collider Dipole Magnets

Part 2: Measurements

This will be the second in a series of notes on the "Ringing" technique for determining turn to turn electrical shorts in magnets. This note will discuss the measurements made during the ringing procedure and the expected signatures of various failure modes.

During a ring a potential difference across a coil or magnet is established which is equal to:

$$V = L \, dI/dt$$

where L is the inductance. To a good approximation this potential difference divides up evenly between the turns, hence the turn to turn voltage is:

$$V_n = (L/n) \quad dI/dt$$

where n is the number of turns. If there is poor insulation integrity between two turns and V_n exceeds the ionization potential of the medium between the turns (usually air during production tests but it could be helium if the magnet is on the test stand) then an electrical short may take place which would not be observable in a standard DC electrical measurement. In the next note we will discuss deviations from this approximation due to the capacitance of the coil.

When a magnet is constructed, the two inner and two outer coils are assembled such that when it is rung the potential difference across the mid-plane of the inner coils is equal to the total drop across the magnet. In other words if the maximum ringing voltage is 2 kV then the maximum voltage drop across the inner coil midplane insulation is also 2 kV. Since the collar assemblies are grounded, the full potential also appears across the coil to collar insulation near the midplane. Therefore there are three failure modes for a full magnet assembly (coil to ground, coil to coil, and turn to turn) and one failure mode (turn to turn) for free coils.

There are several ways in which a failure can make itself known, depending on the subtlety of the short. To date at Fermilab, all failures have been detected by the audible "pop" which has accompanied them. This was the case for the one free coil which failed and for two magnets, DC0303 and DC0304, which failed by shorting across the midplane. The oscilloscope trace obtained when DC0304 failed is shown in figure 1. It should be emphasized that none of these failures was caused by the ringing technique, but rather ringing exposed problems with the magnet components. The free coil was observed to have a DC electrical short when compressed in the collaring tooling but which disappeared when released from pressure. The ringing procedure was used to localize the position of the short. DC0303 and DC0304 had been over compressed near their ends during the keying process and this damaged the midplane insulation. Ringing of the magnet did not stress the insulation beyond what could reasonably be expected during a quench in a string of accelerator magnets. (Since single magnet tests do not stress the insulation as much as would be the case in a string, and since it was known that DC0304 shared the same construction problem as DC0303, DC0304 was not rung above 300 V until after it was tested. At that time it successfully passed a 100 V ring but failed a 500 V ring. It is this final sequence of tests of DC0304 which are shown in figure 1.) Discovery of the weak insulation with the ringing procedure prevented further potentially more serious problems in addition to aiding in the investigation of the cause of the insulation damage.

We will now discuss some of the more subtle failure modes. The measurement procedure which is used calls for ringing the coil or magnet at a succession of voltages, beginning low and working upward. The idea is to establish a baseline measurement at low voltage where a failure is not expected and then to look for deviations as high voltages are tried. Each ring is recorded using a digital display oscilloscope and the results of all rings are overlaid. Figure 2 shows an example of a ring sequence. Variations in the ringing frequency are expected from electrical shorts which result in changes (generally a drop) in the inductance and Q of the coil. From equation 5 of part 1 of these notes we can calculate the change in the cross-over time (the cross over time is the time at which the voltage crosses zero) for a given change in L and Q. Figure 3 shows contour plots of the change in the zero crossing time over a range of L and Q values for free inner and outer coils and for a yoked magnet. Since the inner (outer) coil traces are being recorded on a 100 (200) µs/div time scale it is possible to discern changes in cross over position with a resolution of ≈ 5 (10) µs. The zero volt baseline can be determined with a resolution of ±5 volts. Together this implies that changes of ≥ 2% in inductance (assuming Q does not change much) will be observable. Similarly, since the time scale needed to look at ≈1/4 wavelength of a ring from a yoked magnet is 500 μs/div, changes in cross-over of ≥25 μs (or ≥ 2% changes in inductance) should be observable. In figures 4-6 we show simulations of expected patterns we would obtain if a failure at the threshold of sensitivity occurred.

It is also possible that a turn to turn short or arc might initially occur at high voltage and then disappear as the voltage across the coil decreased during the evolution of the ring. An inspection of the oscilloscope trace should be made for any kinks or transient structure which would be an indication of a sudden change in inductance occurring during a ring.

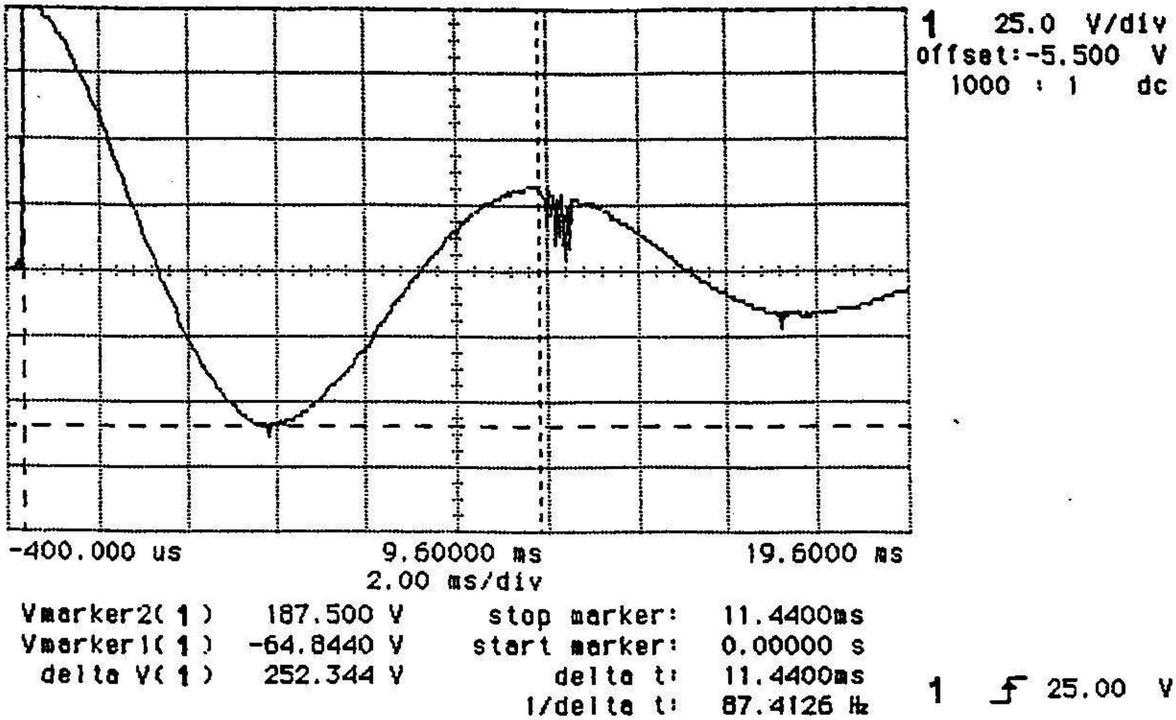

Figure 1a. The ring wave form of DC0304 at 100 V maximum prior to midplane insulation breakdown. The structure at the second maximum is related to the SCR turning on and not to any problem with the magnet.

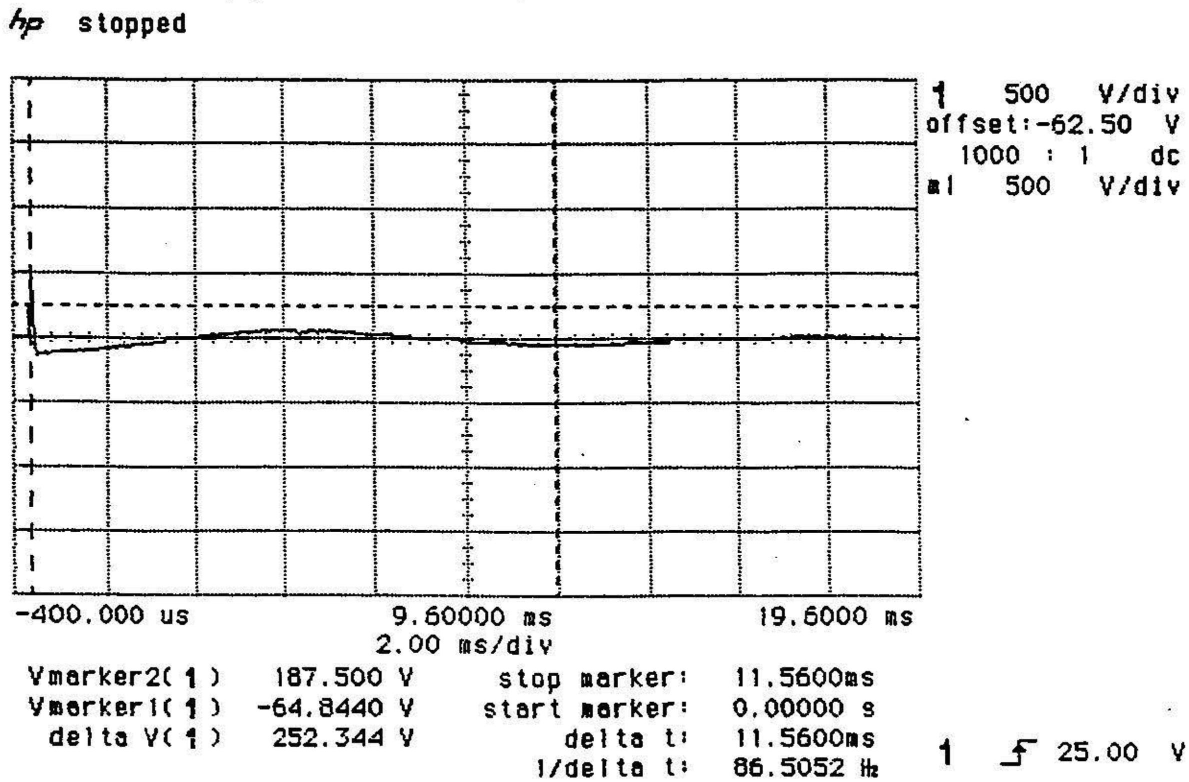

Figure 1b. The ring wave form of DC0304 at 500 V maximum showing midplane breakdown. Note the very rapid drop in voltage after the short developed, the overshoot and eventual low voltage ringing which indicates that below a certain ionization potential their is no indication of an electrical problem. The DC resistance of this magnet did not change appreciably after this test was completed.

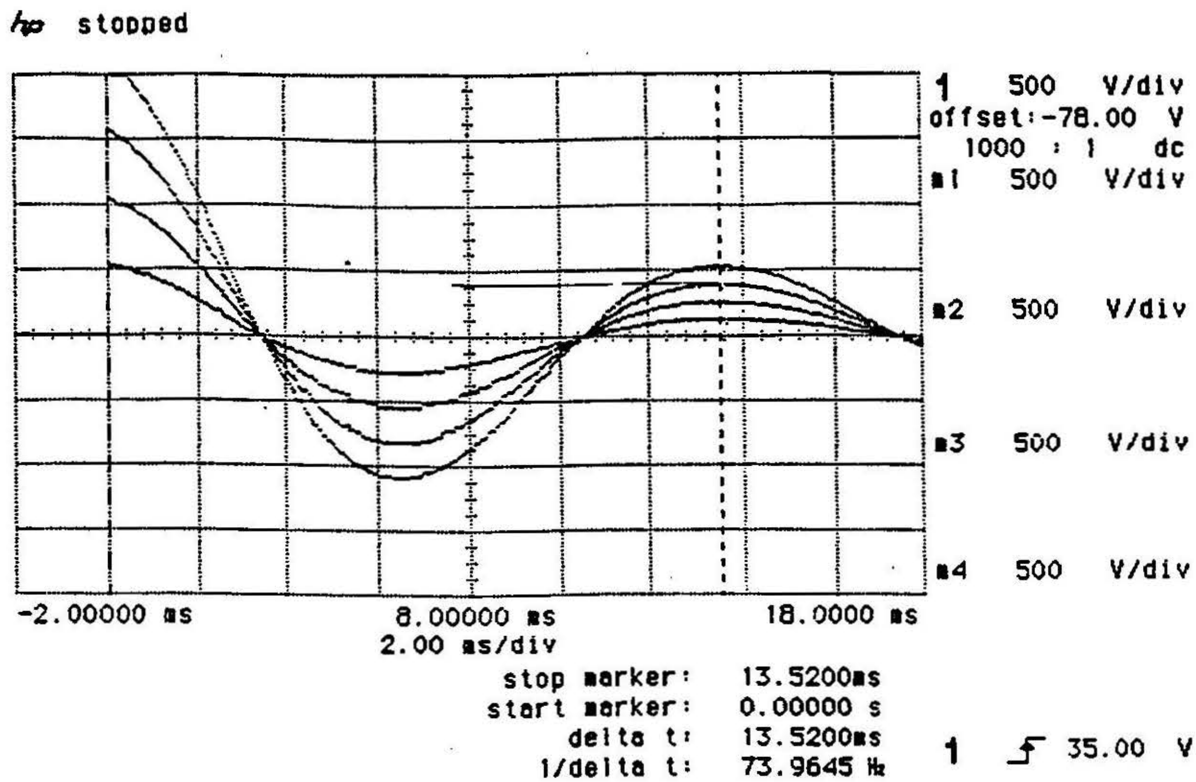

Figure 2. A typical ring sequence is shown for a magnet showing over 1 complete wavelength. Note that all four test waveforms converge at the same zero crossing position.

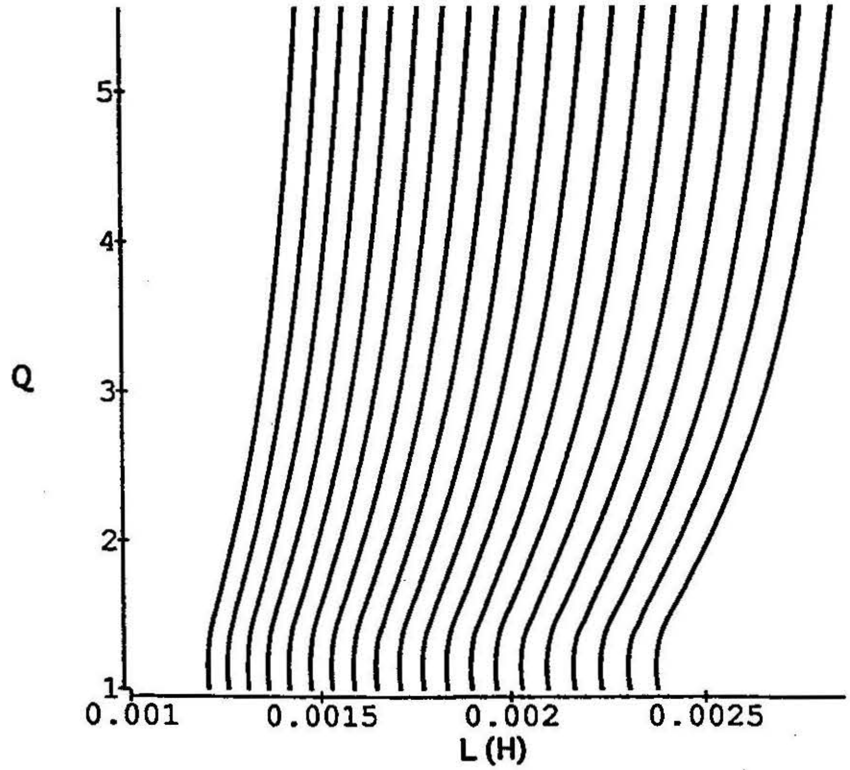

Figure 3. This contour plot indicates how the first zero volt crossing time varies as a function of both inductance (L) and Q for a 50 mm aperture, 15 m long inner coil. The nominal L and Q values give a time corresponging to the upper right corner of the plot. Deviations from this time due to downward changes in L and Q are indicated by the bands, which are in 10 µs steps.

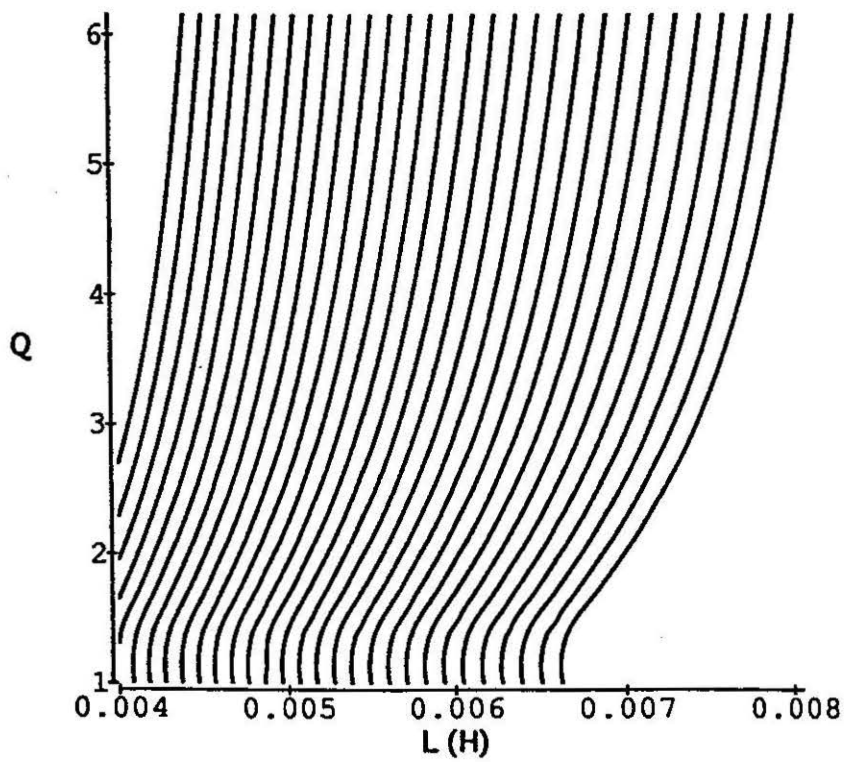

Figure 4. Variations in the first zero volt crossing time for 50 mm aperture, 15 m long outer coils are indicated. The bands are in 10 µs steps.

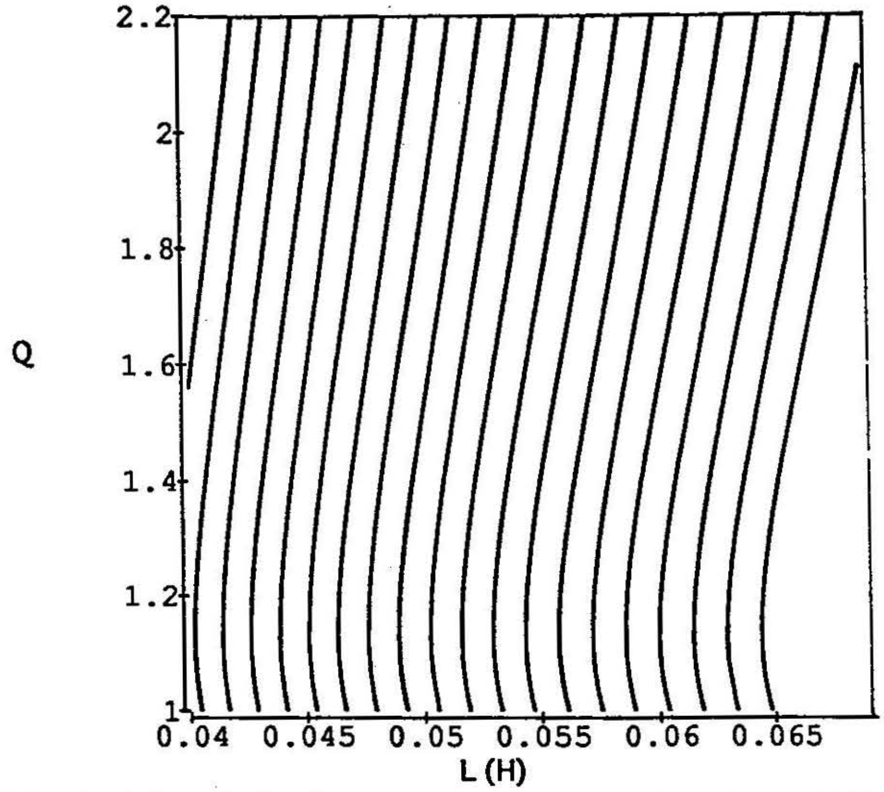

Figure 5. Variations in the first zero volt crossing time for a yoked 50 mm aperture, 15 m long magnet are indicated. The bands are in 40 μs steps.

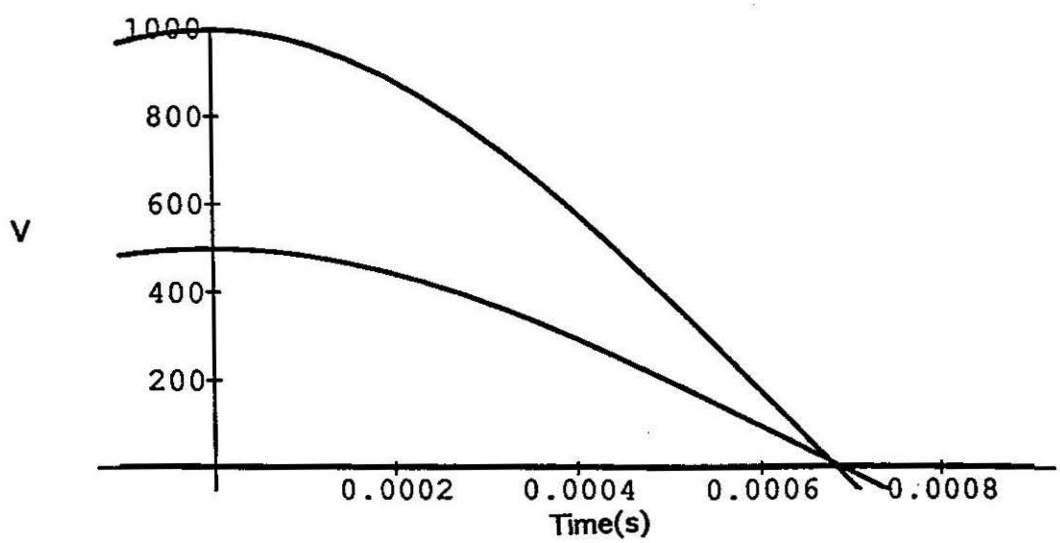

Figure 6. This plot shows a simulation of the effect on the signal trace from a 2% drop in inductance of a 50 mm aperture, 15m long inner coil when being rung at 2 kV as compared to the signal trace from a 1 kV ring with nominal L and Q. The broadened horizontal axis indicates the resolution on the zero volt baseline. The two traces clearly do not cross the baseline at the same position.

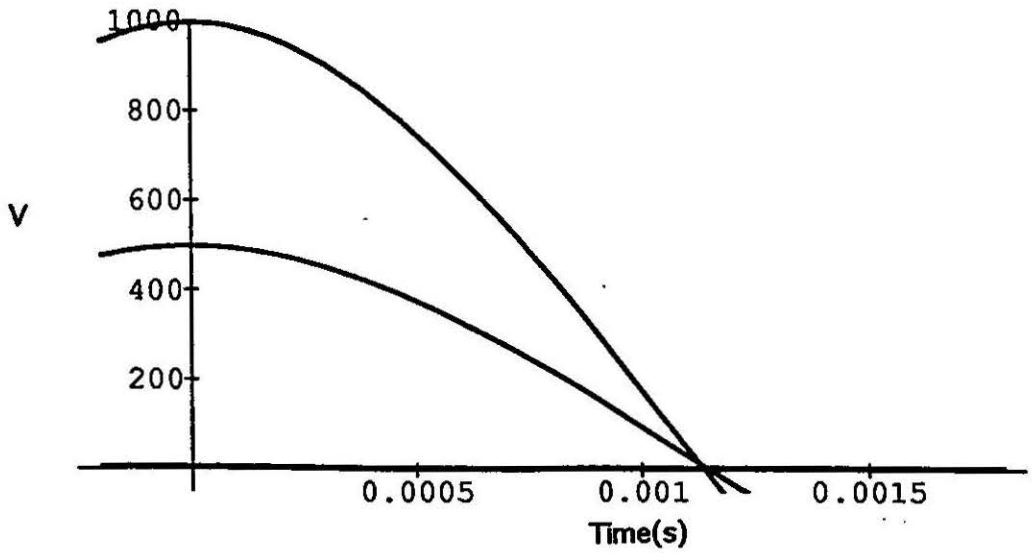

Figure 7. A simulation of the effect on the signal trace from a 2% drop in inductance of a 50 mm aperture, 15 m long outer coil when being rung at 2 kV as compared to a signal trace from a 1 kV ring with nominal L and Q.

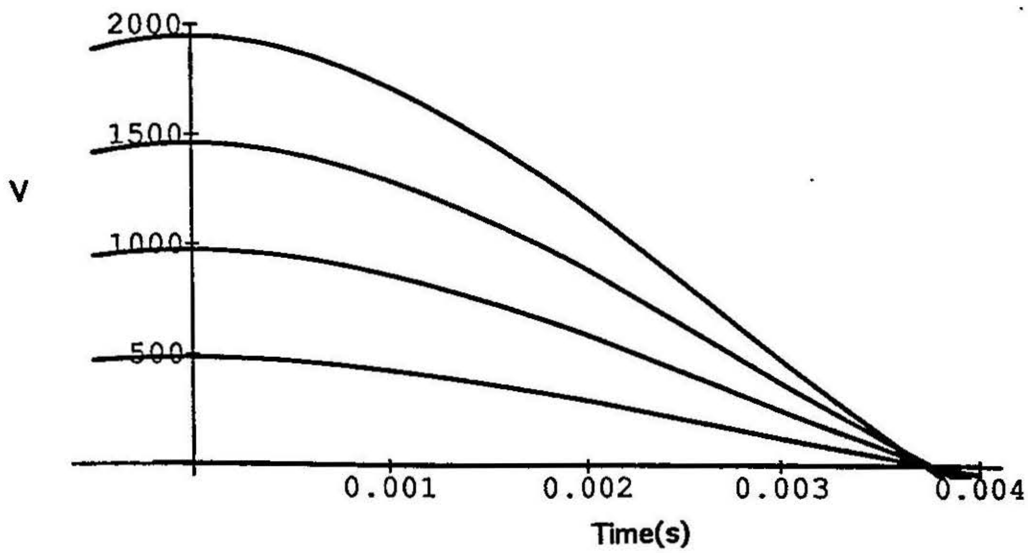

Figure 8. A simulation of the effect on the signal trace from a 2% drop in inductance of a 50 mm aperture yoked magnet being rung at 2 kV as compared to signal traces at 500, 1 kV and 1.5 kV rings with nominal L and Q.