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

Part 3: The Magnet as a Lumped LCR Circuit

In the first two notes of this series we made the assumption that the magnet is an inductance with some distributed resistance, however we ignored any intrinsic coil capacitance. This is obviously an oversimplified picture of the magnet. First, the magnet is composed of 4 coils in series, each of which is coupled to the others through mutual inductance. In addition, the capacitance of the individual coils is non-negligible. On an even finer scale, each turn of a coil could be treated as a separate piece of a lumped LCR circuit. Effects of coil capacitance, mutual inductance, etc. have been observed on 40 mm magnets. A series of measurements have been done to observe the propagation of the voltage through a yoked magnet. Measurements were made using two probes, one positioned to measure the total voltage drop across the coil while the second probe was used to measure the drop from various quarter coil positions. These measurements are shown in figures 1-4. One sees that the initial pulse of the ringer excites a high frequency oscillation (with $\tau \approx 10\mu s$) that propagates through the first two coils with substantial amplitude. After two or three oscillations it damps out and is replaced by a much lower frequency oscillation (with $\tau \approx 100\mu s$). This lower frequency oscillation persists for about four cycles before being completely damped out. It can be seen very clearly when looking at the upper and lower coils together as in figure 5. Note that the oscillations are 180° out of phase between the upper and lower coils. It appears from these measurements that the initial high frequency oscillations are an excitation of the inductance- capacitance system of the quarter coils, while the second may be due to the inductance-capacitance of the half coils with some coupling through mutual inductance.

The initial high frequency oscillation was subsequently studied in more detail on DC0306 which was assembled with special voltage taps on the first turns of the inner coils (taps on turns 1,3,5,7 and 9). The tap on turn 3 became disconnected before these measurements were made. Figure 6 shows the voltage drop across the inner coil. It looks the same as that of DC0301. Figure 7 shows the voltage drop across turns 1, 5, 7, and 9. It can be seen that the voltage drop across the turns of the inner coil divides up fairly evenly. Therefore the maximum voltage drop across turns is approximately 1/16 of the maximum drop across the inner coil, which is ≈60% of the full ring voltage. So for a 2 kV ring, the maximum turn to turn voltage would be $1/16 * 0.6 * 2000\ V = 75\ V$ over $\leq 5\mu s$. If we do not assume the voltage divides evenly between all turns, and attempt to get an upper limit on the maximum voltage between turns directly from figure 7, we see that the voltage drop between turns 5 and 7 can briefly be as large as 18 V for a 100 V ring, implying that for a 2 kV ring the drop could be about 180 V between turns.

To summarize, the voltage drop between coils in a magnet, and between turns in a coil, does not divide evenly. One may expect to see up to 10% of the maximum voltage used in a ring test appear between two turns in a coil for a period of a few microseconds. Therefore, one must determine that the electrical insulation between turns is adequate to withstand this voltage when determining the maximum voltage which will be applied to a magnet. However, the insulation currently used in magnets should be sufficient to withstand maximum ring voltages of 2000 volts without failure, unless it has been previously damaged in some way.

Magnet DC0301

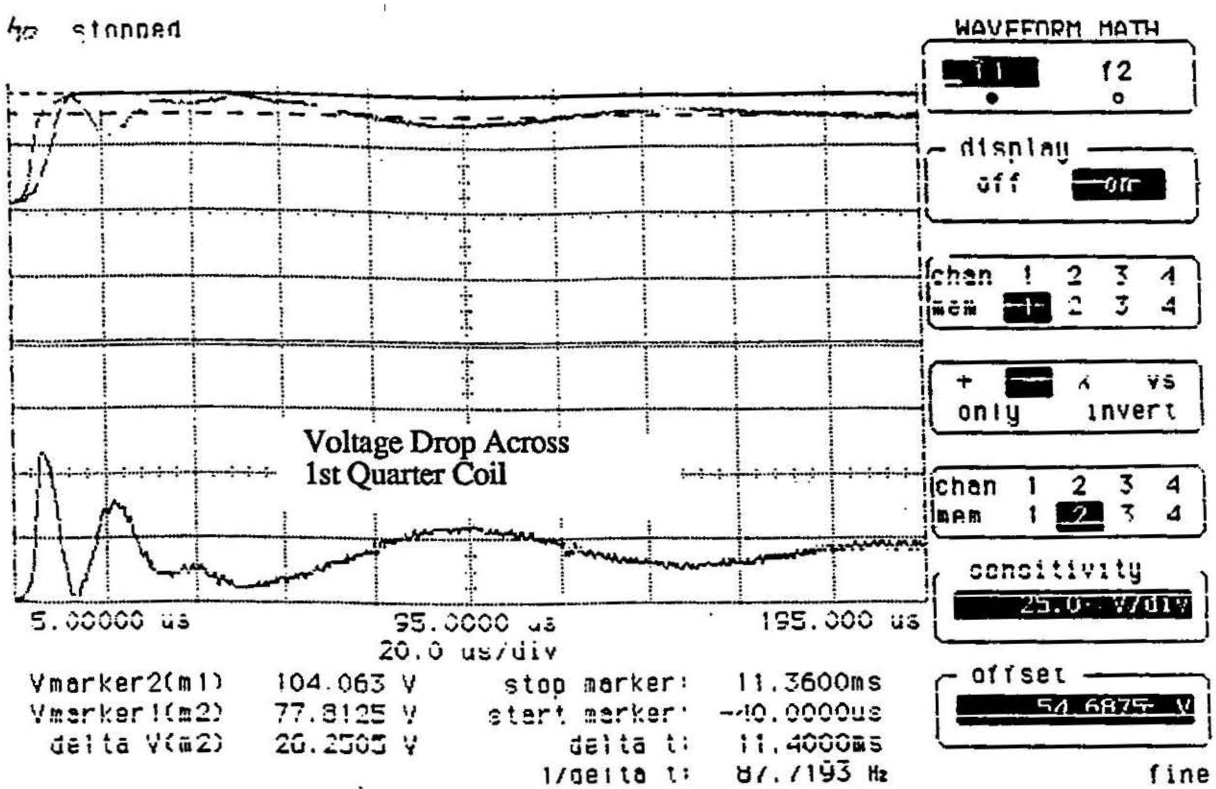

Figure 1. Voltage drop across the 1st quarter (inner) coil of magnet DC0301 as determined by subtracting the voltage drop across the last 3 quarters of the magnet from the voltage drop across the full magnet. The upper screen shows the voltage drop across the full magnet and the drop across the last 3 quarters. The bottom screen shows the derived voltage across the 1st quarter coil.

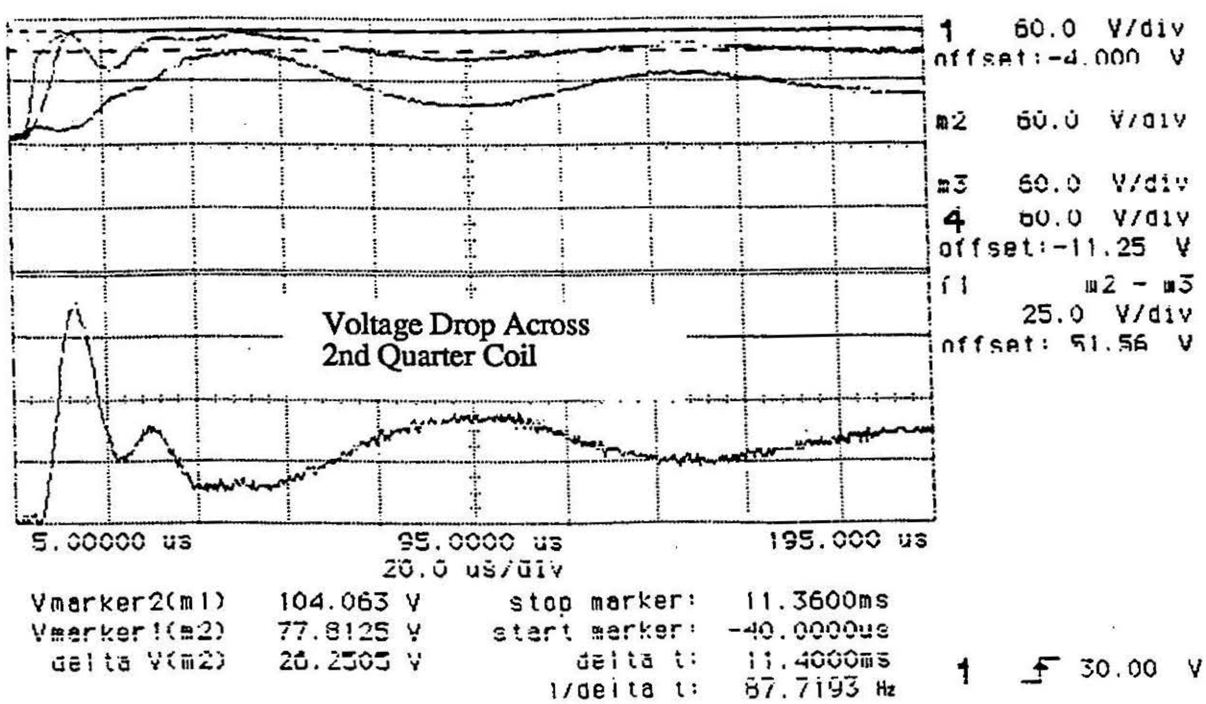

Figure 2. Voltage drop across the 2nd quarter (outer) coil of magnet DC0301 as determined by subtracting the voltage drop across the last 2 quarters of the magnet from the voltage drop across the last 3 quarters.

Magnet DC0301

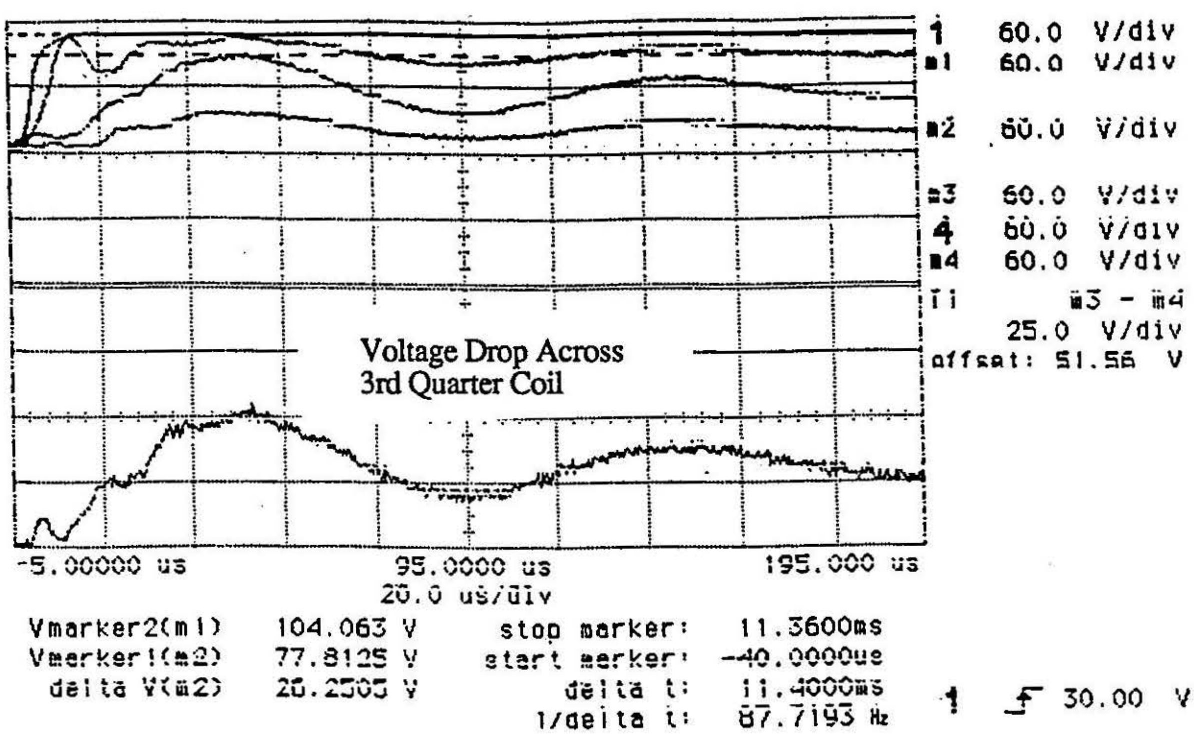

Figure 3. Voltage drop across the 3rd quarter (outer) coil of magnet DC0301.

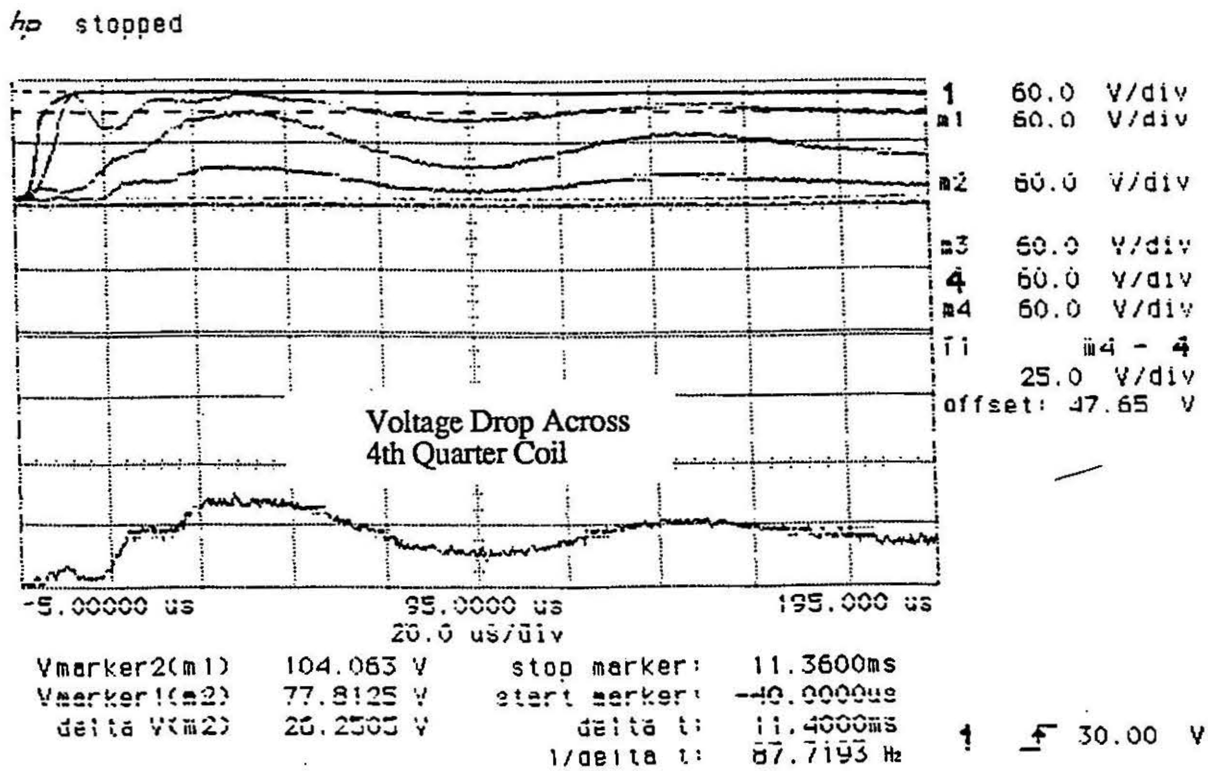

Figure 4. Voltage drop across the 4th quarter (inner) coil of magnet DC0301.

Magnet DC0301

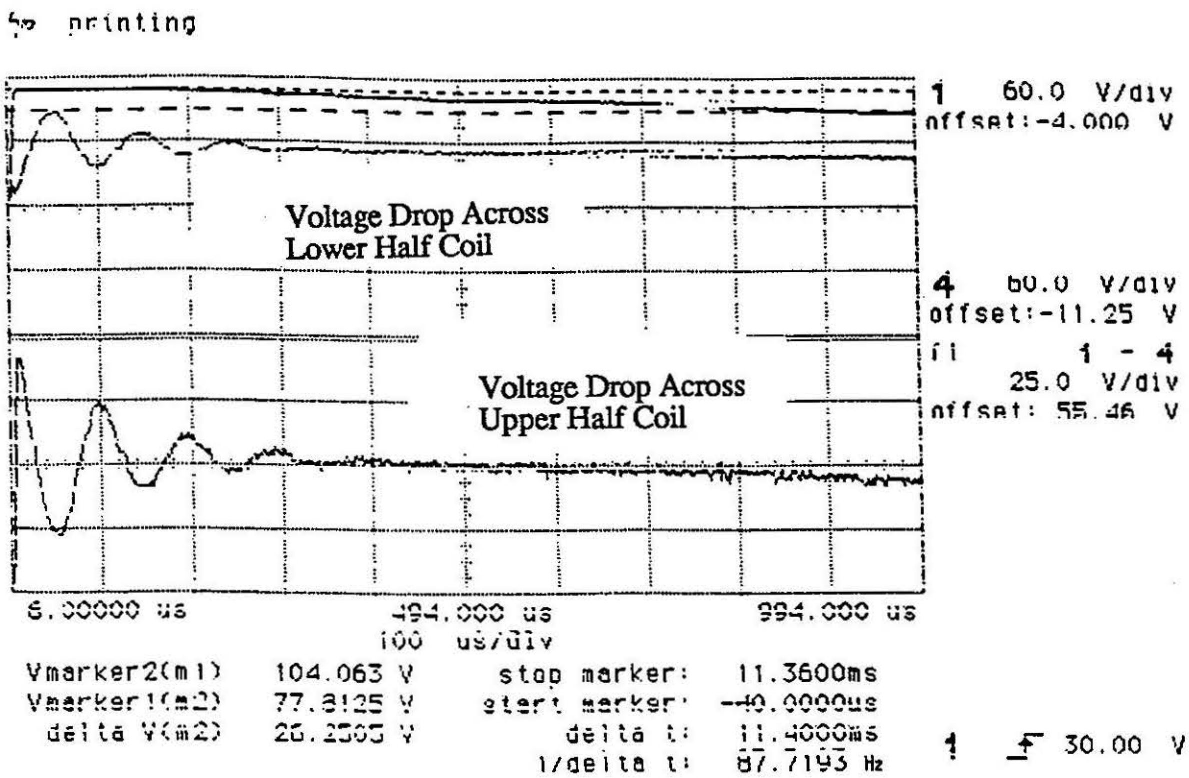

Figure 5. Voltage drop across the upper and lower half coils of magnet DC0301.

Magnet DC0306

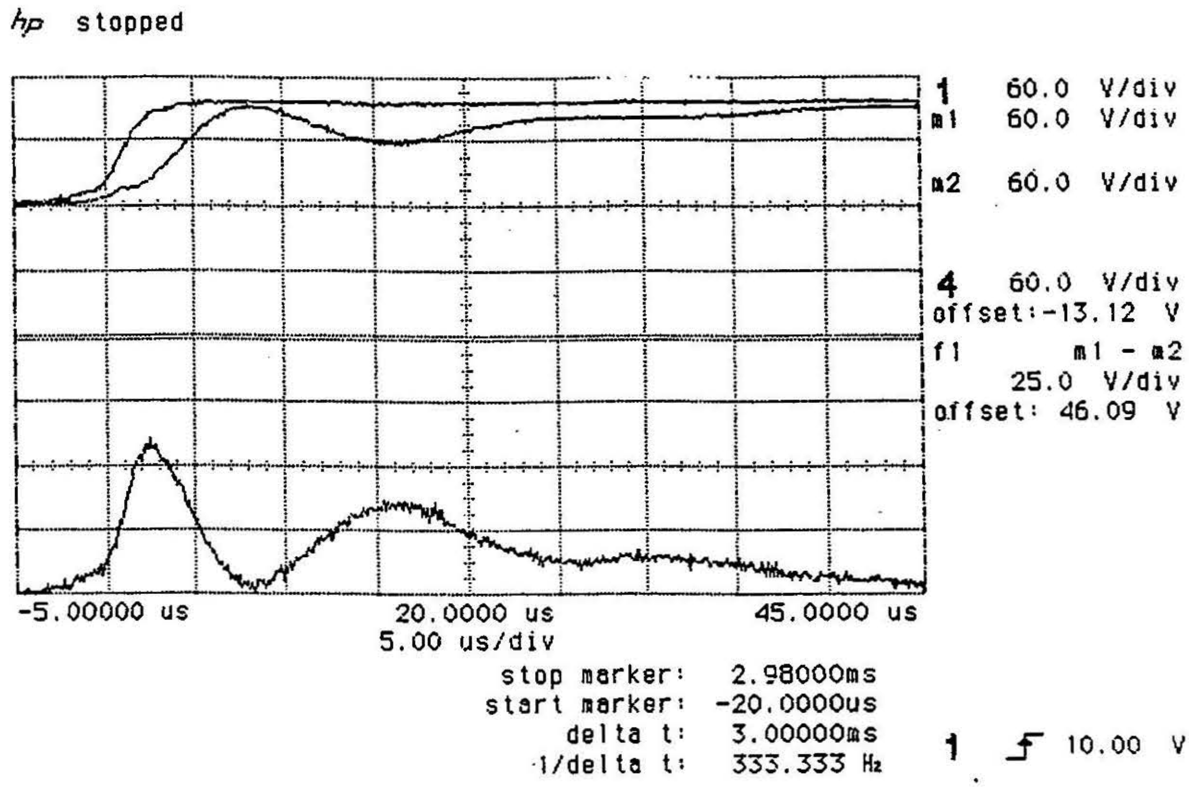

Figure 6. Voltage drop across the 1st quarter (inner) coil of magnet DC0306.

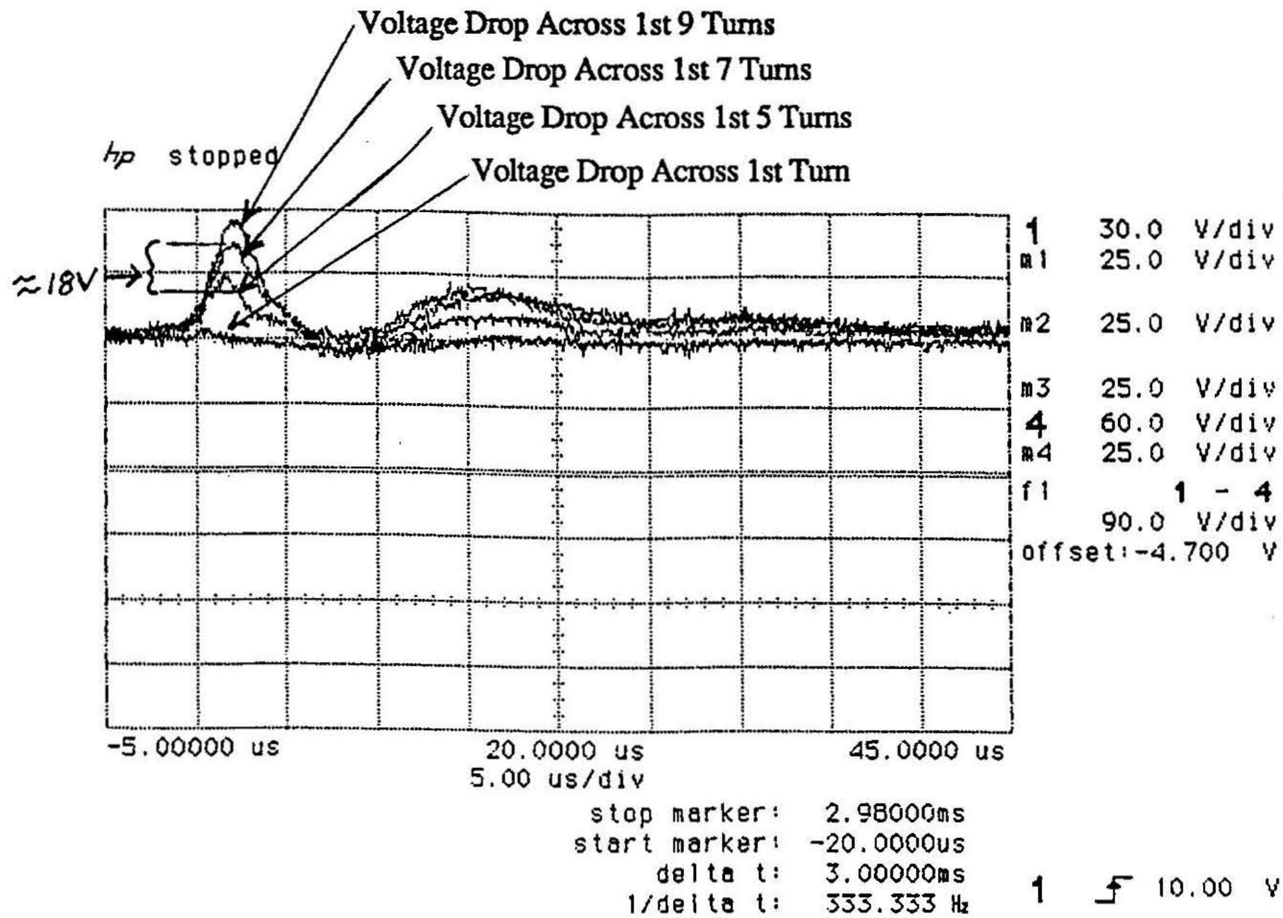

Figure 7. Voltage drops across the first several turns of the 1st quarter coil of magnet DC0306.