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

Part 1: Basic Equations

This will be the first in a series of notes on the "Ringing" technique for determining turn to turn electrical shorts in magnets. This technique has been used extensively at Fermilab and Brookhaven National Laboratory to determine the integrity of coils and magnets[1]. In these reports, I will document how we are using this technique with respect to the SSC magnets being built at Fermilab. This note will contain a general description of the hardware and procedure and will summarize the formulas used to predict the response of the coils to ringing.

The purpose of the ring test is to develop a sufficient potential difference between adjacent turns of a coil so that a spark can develop if the insulation has been damaged in any way. This is accomplished by discharging a capacitor across the coil so that the inductive voltage across the entire coil is large enough that when it is divided by the number of turn the voltage per turn is above the ionization potential of air (about 25 volts). The test is currently performed on free coils, collared coil assemblies and the final cold mass assembly.. The circuit for the ring test is schematically shown in figure 1. A capacitor, (nominally a capacitor bank with 60 μf equivalent capacitance) is charged to some voltage by a high voltage power supply. It is then discharged across the coil or magnet through an SCR diode configuration (SCR is continuously triggered so that it stays on once initially fired). A digitizing oscilloscope records the voltage levels. Any change in the coil inductance (due to a short) will change the frequency of the waveform and therefore it can be detected by this technique.

When the capacitor is discharged in the procedure outline above, the voltage across it exhibits a damped harmonic oscillation[2], as shown in figures 2 and 3. Assuming we ignore the circuit resistance relative to the coil, it is this voltage which is measured by the oscilloscope. The equation describing this damped oscillation is:

$$V = V_0 \exp\left(\frac{\gamma t}{2}\right)\cos(\omega t + \alpha)$$

where

$$\omega = \omega_0\left(1 - \frac{1}{4Q^2}\right)^{\frac{1}{2}}$$

1) $$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Q = \frac{\omega_0}{\gamma} = \omega_0 \frac{L}{R}$$

Both the inductive and resistive components of the impedance can vary as a function of frequency[3], as can be seen from data obtained with an LCR meter for coils and yoked magnets and compiled in tables 1 and 2 and shown in figures 4 and 5. We can use these formula to calculate the expected ring frequency of coils or magnets being tested. For the example shown in figure 2, we see that the oscillation frequency is approximately 80 Hz, corresponding to an inductance and Q, measured at low voltage with the LCR meter, of 69 mH and 2.2, respectively. The measured capacitance of the ringer test set is 61 μf, and we ignore all circuit resistance other than that of the magnet. Using these values we calculate an expected ring frequency of 75.5 Hz. The measured frequency is 74 Hz. Therefore we conclude that this magnet does not show signs of a change in inductance at the turn to turn voltages induced by the ringer test set that could be indicative of a turn to turn short.

For the example in figure 2, one may also calculate from Eq. 1 that the voltage at the second maximum, V_{2m}, should be down from the initial peak voltage by a factor of 0.231 as follows:

2) $$V_{2m} = V_0 \exp\left(-\frac{\gamma t_{2m}}{2}\right) = V_0 \exp\left(-\frac{\omega_0 t_{2m}}{2Q}\right).$$

Since

$$t_{2m} = \frac{2\pi}{\omega}$$

we may write

$$V_{2m} = V_0 \exp\left(-\frac{\pi}{\left(Q^2 - 1/4\right)^{\frac{1}{2}}}\right)$$

$$= 0.231 V_0 \qquad \text{when } Q = 2.2.$$

When a ring test is performed on a free coil, the time base of the oscilloscope is set such that only ≈ 1/4 of a wavelength is shown in order to improve resolution. An example of this measurement is shown in figure 3. The time required for the voltage across the coil to drop from its maximum to zero is not 1/4 the period of the oscillation. To determine this time, note that from Eq. 1:

3) $$\frac{dV}{dt} = -V_0 \exp\left(-\frac{\gamma t}{2}\right)\cos(\omega t + \alpha)\left[\frac{\gamma}{2} + \omega \tan(\omega t + \alpha)\right].$$

Setting the initial condition such that V is maximum at t = 0 implies that

4) $$\alpha = \tan^{-1}\left(-\frac{\gamma}{2\omega}\right)$$

From Eq. 1, V=0 when

$$\omega t + \alpha = \frac{\pi}{2}.$$

Therefore Δt, the time between the maximum voltage and the first zero crossing point is:

$$\Delta t = \frac{1}{\omega}\left(\frac{\pi}{2} - \tan^{-1}\left(-\frac{\gamma}{2\omega}\right)\right)$$

5) or

$$\Delta t = \sqrt{LC}\left(1 - \frac{1}{4Q^2}\right)^{-\frac{1}{2}}\left[\frac{\pi}{2} - \tan^{-1}\left(\frac{1}{(4Q^2-1)^{\frac{1}{2}}}\right)\right]$$

To determine Δt for the example in figure 3 we calculate the undamped oscillation frequency f, which is 380 Hz. At this frequency, L=2.87 mH and Q≈5.8 mH. Inserting these values into the above equation yields a value for Δt of 691 µs, in good agreement with the measured value of 688 µs.

Finally, for completeness we note that:

6)

$$\begin{aligned} I &= C\frac{dV}{dt} \\ &= -V_0 C \exp\left(-\frac{\omega_0 t}{2Q}\right)\cos\left(\omega_0\left(1-\frac{1}{4Q^2}\right)^{\frac{1}{2}} + \tan^{-1}\left(-\frac{1}{4Q^2-1}\right)^{\frac{1}{2}}\right) \\ &\times\left(\frac{\omega_0}{2Q} + \omega_0\left(1-\frac{1}{4Q^2}\right)^{\frac{1}{2}}\tan^{-1}\left(-\frac{1}{4Q^2-1}\right)^{\frac{1}{2}}\right) \end{aligned}$$

Frequency (Hz)	Inductance (L) (mH)	Q Factor	Resistive Component of Impedance (Ω)
140	60.98	1.98	27
120	63.76	2.07	23
100	66.61	2.16	19
80	69.39	2.22	16
70	70.71	2.22	14
60	71.94	2.18	12
40	74.01	1.89	10
20	75.40	1.17	8

Table 1. Frequency dependence of the inductive and resistive components of SSC dipole magnet DCA310. Measurements of inductance and Q were made with an LCR meter through the power bus.

Frequency	Inner Coil 1016			Outer Coil 2016		
	L (mH)	Q	R (Ω)	L (mH)	Q	R(Ω)
100	2.88	1.65	1.10	8.04	2.77	1.82
200	2.87	3.22	1.12	8.04	5.47	1.85
300	2.88	4.70	1.16	8.03	8.03	1.89
400	2.87	6.07	1.19	8.03	10.4	1.94
500	2.87	7.30	1.24	8.03	12.6	2.00
600	2.86	8.34	1.29	8.02	14.6	2.07
800	2.86	9.31	1.54	8.03	16.4	2.46
1000	2.84	11.7	1.53	8.00	20.7	2.43

Table 2. Frequency dependence of the inductive and resistive components of free inner and outer dipole magnet coils. These values are not expected to change significantly from coil to coil so we can treat them as representative of all coils.

Frequency (Hz)	Inductance (L) (mH)	Q Factor	Resistive Component of Impedance (Ω)
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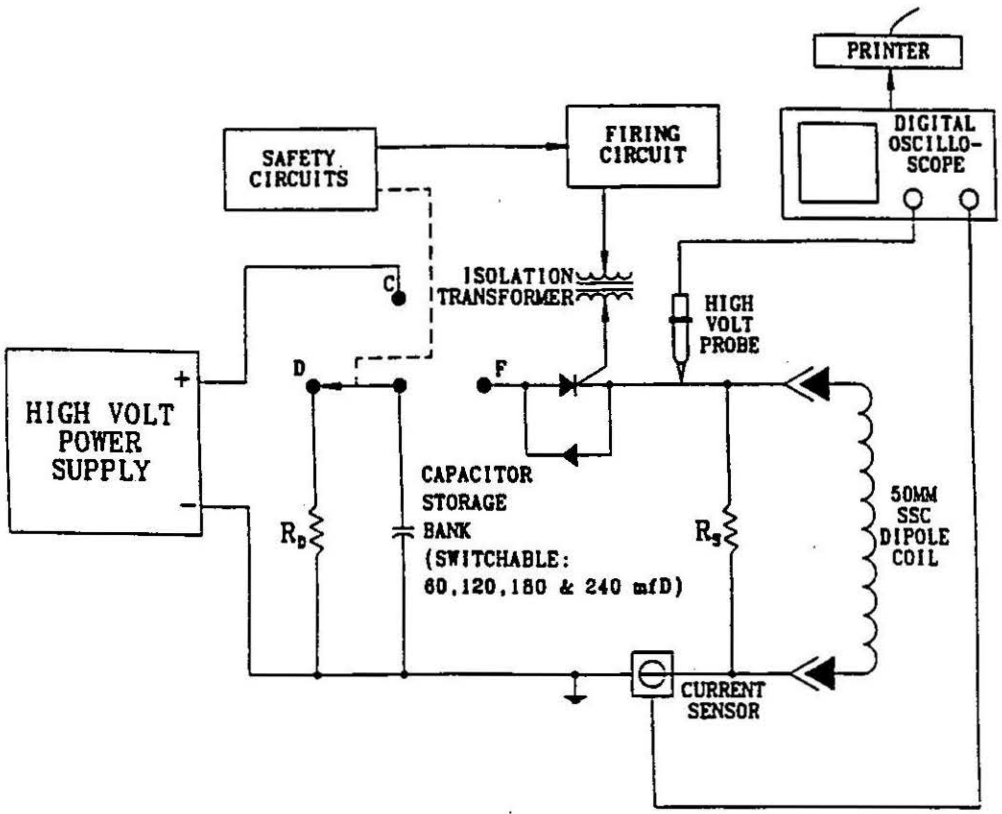
1 G.F. Sintchak, J.G. Cottingham and G.L. Ganetz, Electrical Insulation Requirements and Test Procedures for SSC Dipole Magnets, Supercollider 2, 397 (1990) M. McAshan, ed.; P. Mazur, private communication.

2 See, for example, A.P. French, Vibrations and Waves, The MIT Introductory Physics Series, W.W. Norton and Company, Pub, page 365.

3 R.E. Shafer, Eddy Currents, Dispersion Relations, and Transient Effects in Superconducting Magnets, Fermilab TM-991, 9-22-80.



BASIC SCHEMATIC OF COIL RINGING TEST SET

Figure 1. The basic components of the high voltage coil ringing test set.

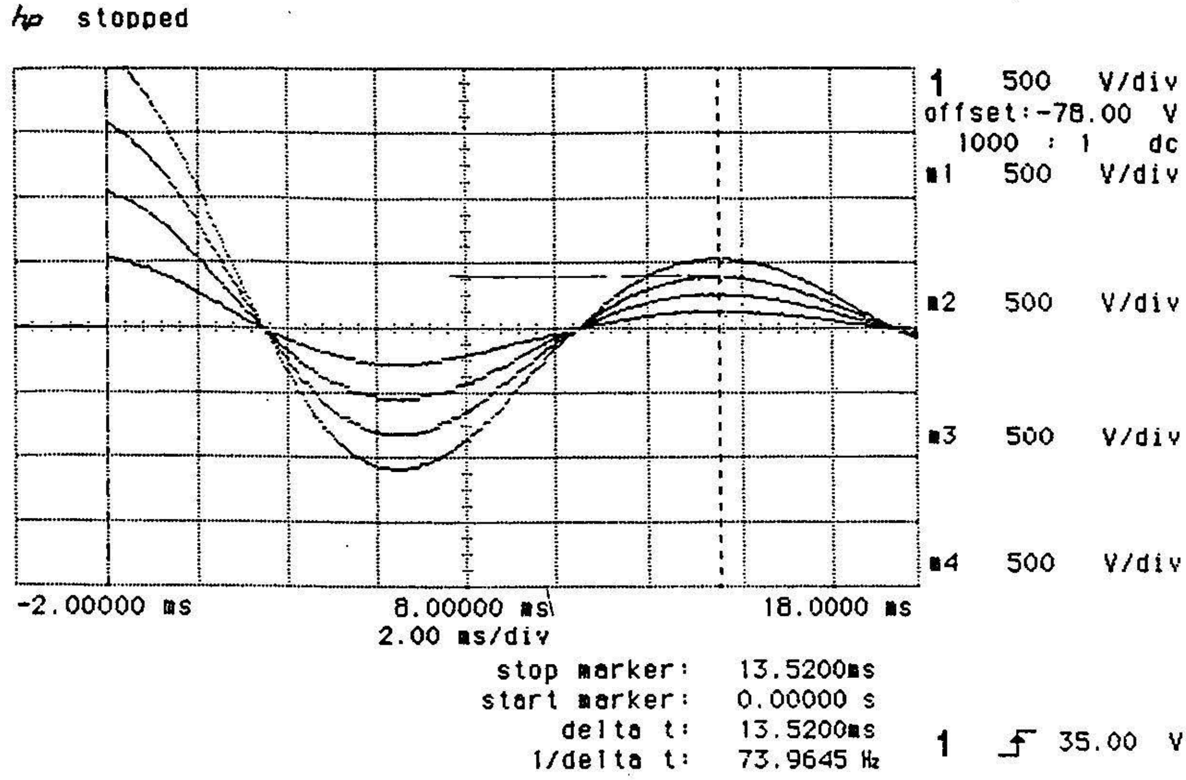


Figure 2. An oscilloscope display of a "ringing" measurement at 4 different voltages of a completed SSC dipole magnet performed at room temperature. The initial voltages were approximately 500, 1000, 1500 and 2000 V.

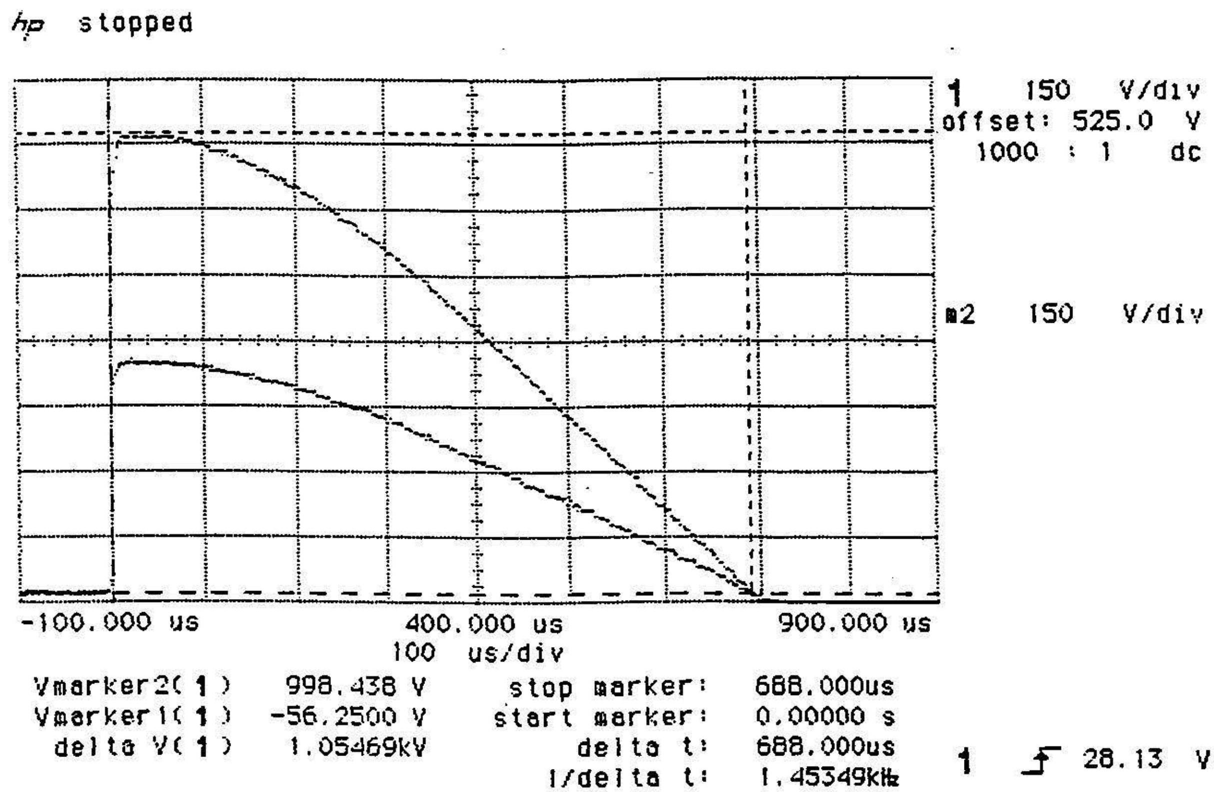
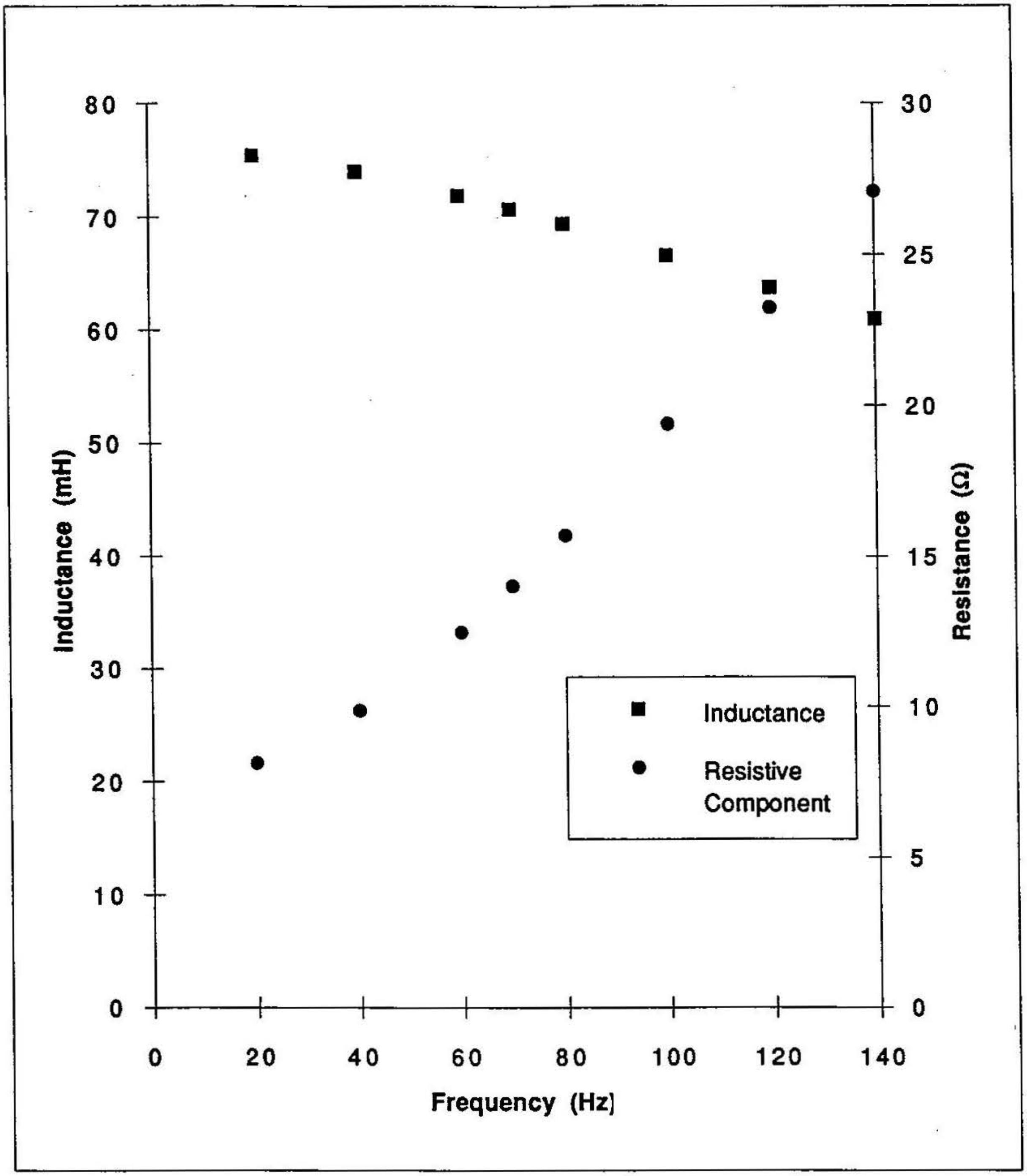
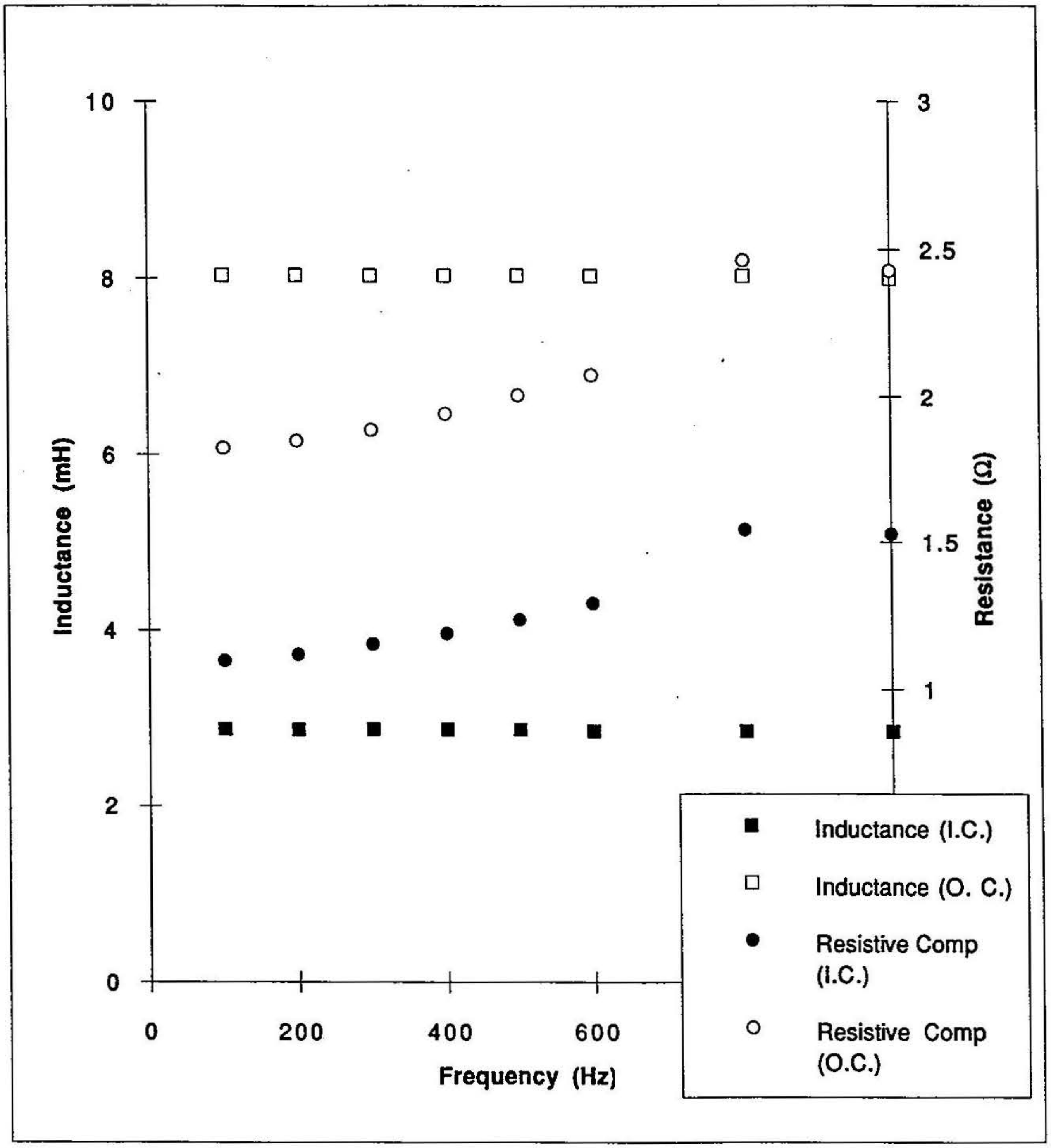


Figure 3. An oscilloscope display of a "ringing" measurement at 2 different voltages of a free SSC dipole coil. The initial voltages were approximately 500 and 1000 V.



Inductive and resistive components of the impedence of a warm SSC superconducting dipole magnet (DCA310) as functions of frequency.

Figure 4.



Inductive and resistive components of the impedence of inner (I.C.) and outer (O.C.) coils from SSC superconducting dipole magnets as a function of frequency. (Coils 1016 and 2016)

Figure 5.