Fermilab

UPC 127

NON-LINEAR CHARACTERISTICS OF THE DOUBLER MAGNET YOKE INDUCTANCE

R. Shafer

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Whenever there is a net current linking the yoke of the Doubler dipole magnet, there is a toroidal magnetization of the steel. As pointed out earlier[1] this leads to a large self and mutual inductance of both the coil bus and return bus circuits. As the magnetizing force H can reach nearly 100 oersteds when the net linking current is 4500 amps, a highly non-linear behavior is expected when the return bus and the coil bus currents are dumped with different time constants. The purpose of this note is to calculate approximately what the yoke inductance is as a function of net linking current, and to calculate the quench discharge characteristics of the magnet system when this non-linear inductance is included.

Let us consider the yoke to be a toroid of 19 cm inside diameter, 28 cm outside diameter, and 6 m long. This geometry is obviously somewhat different than the actual yoke, but lends itself to easy calculation.

In mks units B and H are related by

$$B = \mu\mu_0 H, \tag{1}$$

where $\mu_0 = 4\pi\times10^{-7}$ Henrys/meter, $H = I/2\pi r$, and

$$\mu = \frac{\alpha + \mathcal{H}}{\beta + \mathcal{H}}; \qquad \mathcal{H} = 4\pi\times 10^{-3} H \quad \text{(c.g.s. units)}. \tag{2}$$

B is plotted vs H in Fig. 1 using $\alpha = 21{,}500$ and $\beta = 10$.

We may write B as a function of I and r (tesla, amps, meters):

$$B = \frac{2\times 10^{-7}}{r}\left[\frac{500\alpha r + I}{500\beta r + I}\right] I. \tag{3}$$

Then

$$\frac{\partial B}{\partial I} = \frac{2\times 10^{-7}}{r}\left[\frac{500^2\alpha\beta r^2 - 500^2\beta^2 r^2 + (500\beta r + I)^2}{(500\beta r + I)^2}\right]$$

$$\simeq \frac{2\times 10^{-7}}{r}\left[1 + \frac{500^2\alpha\beta r^2}{(500\beta r + I)^2}\right]. \tag{4}$$

Since

$$\frac{dB}{dt} = \frac{\partial B}{\partial I}\frac{dI}{dt} \quad \text{and}$$

$$\frac{d}{dt}\int B\cdot dA = \frac{dI}{dt}\int \frac{\partial B}{\partial I}\, dA = L(I)\frac{dI}{dt}$$

$$L(I) = \int \frac{\partial B}{\partial I}\, dA = 2\times 10^{-7} z \int_{r_1}^{r_2} \frac{1}{r}\left[1 + \frac{500^2\alpha\beta r^2}{(500\beta r + I)^2}\right] dr, \tag{5}$$

where $r_1 = 0.095$ m, $r_2 = 0.14$ m, $z = 6$ m, $\alpha = 21{,}500$, and $\beta = 10$. Carrying out the integration we get for the inductance of a single Doubler dipole magnet yoke:

$$L(I) = 1.2\left[0.39 + 2150\left\{\ell n\left(\frac{700 + I}{475 + I}\right) - \frac{225I}{(700 + I)(475 + I)}\right\}\right]\mu H. \tag{6}$$

For the range of interest here, an adequate approximation is

$$L(I) = \frac{350}{(I + 600)^2} \text{ Henrys.} \tag{7}$$

This ranges from nearly 1000 μH at zero current to 13 μH at 4500 A. A plot of L(I) vs. I is presented in Fig. 2.

In Fig. 3 a model of the original magnet circuit is shown. This model, derived earlier,[1] considers all the dipoles to be on one bus (the coil bus) and none to be on the other (the return bus). This model is now analyzed using circuit analysis program SCEPTRE which can include the non-linear yoke inductance. Initial values are 4500 A flowing in the circuit when the power supply (actually 6) is bypassed, the return bus is bypassed, and the dump resistors (actually 7 including the return bus dump resistor) are put into the circuit. Note that the return bus dump resistor in this model is 0.3 ohms.

Figure 4 shows the coil bus current vs. time. The decay time constant is roughly 12 seconds.

Figure 5 shows the maximum coil bus voltage to ground vs. time. Its initial value is roughly 1120 volts.

Figure 6 shows the return bus current vs. time. It is non-exponential since the yoke inductance is changing with time. It decays to 1000 amps in about 0.5 seconds.

Figure 7 shows the net current linking the yoke vs. time. This current which includes the coil bus current, the return bus current, and the induced currents in the cryostat (the yoke acts as a current transformer) rises to a maximum of 4000 amps after about 0.5 sec and decays with a 12-sec time constant.

Figure 8 shows the yoke inductance vs. time. It drops from roughly 800 mH initially to about 10 mH in 0.5 sec, and recovers very slowly as the coil bus current decays away.

Figure 9 shows the induced currents in the cryostat vs. time. The maximum current is nearly 200 amps. This current loop is composed of the vacuum chamber cryostat (stainless steel) which is shorted to the yoke laminations at the ends of the magnet by the inherent design of the magnet, and the "L" beams welded longitudinally along the outside.

Figure 10 shows the net current flowing in the 2 km diameter loop vs. time. It reaches a maximum of about 4000 amps in 0.5 sec and decays with a 12-sec time constant. The peak current corresponds to roughly 25 mG at the center of the ring. This flux change through the loop corresponds to roughly 100 volts per turn induced in the tunnel structure etc. if there were no induced currents.

Figure 11 shows the total $\int I^2 dt$ accumulated in the return bus vs. time. It reaches a maximum of nearly 6 MA^2-sec (miit's) in 0.5 sec. The maximum allowed value is about 7 miit's without damaging the return bus.

The miit's in the return bus can be reduced by increasing the return bus dump resistor to 0.5 ohm from the 0.3 ohm valve used in the analysis. However, it should be recognized that with the 0.3 ohm resistor the maximum coil to return bus voltage stress is about 1800 volts, and this would rise to about 2250 volts if a 0.5 ohm resistor were used. Hence the lower and upper limits on the return bus dump resistor are set by the return bus heating and voltage breakdown respectively. The uncertainty in the yoke inductance is such that the dump resistor cannot be specified at this time, or indeed if more than one return bus dump resistor is required.

It should be pointed out in conclusion that this analysis does not include any allowance for remnant magnetic field in the yoke (hysteresis) which could greatly influence the low current inductance characteristics, nor does it include the fact that the coil dipole field can also influence the inductance characteristics. These effects are best explored by actual measurements on magnets. They would have to be done at very low frequencies due to the ubiquitous presence of the cryostat short linking the yoke.

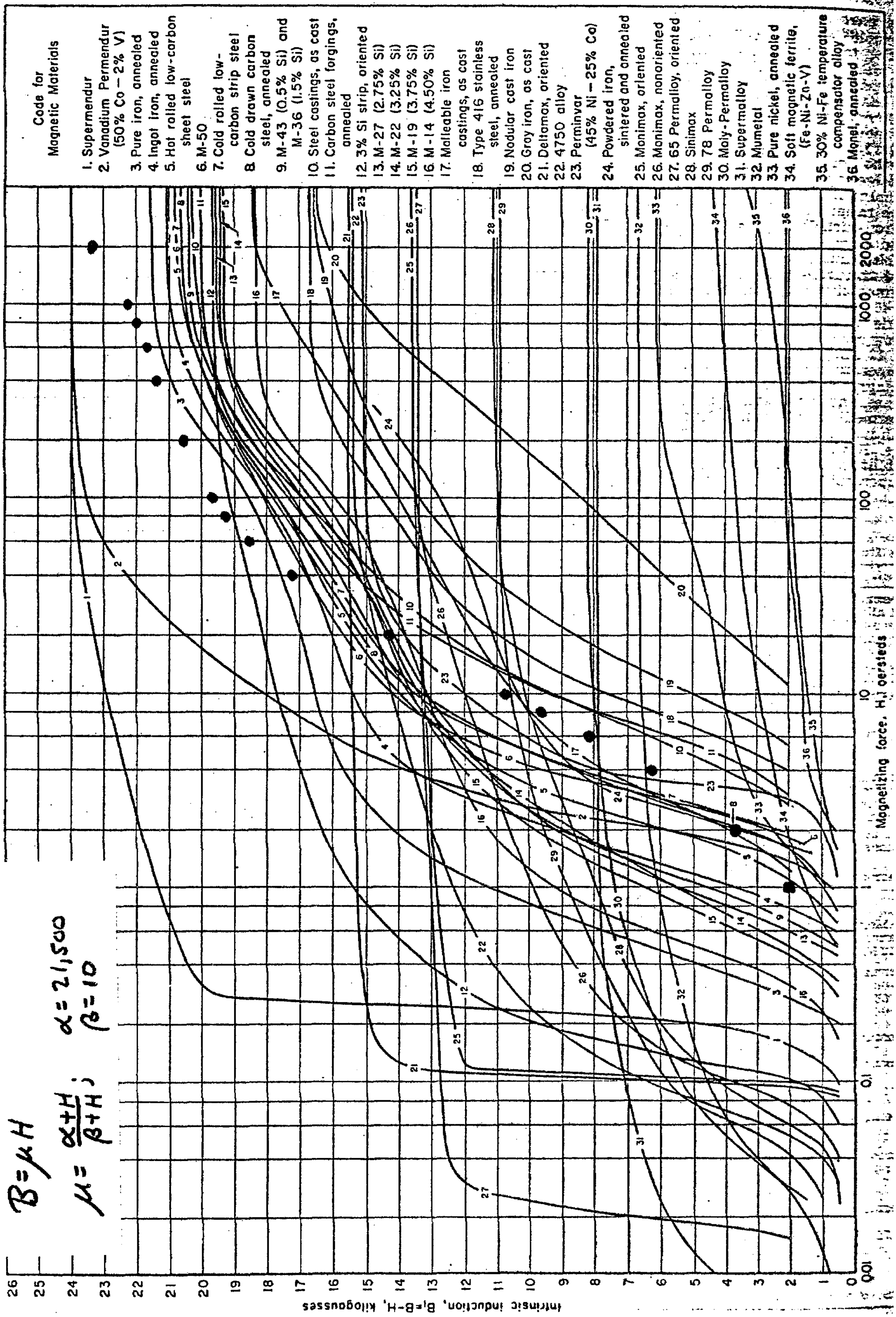
Reference

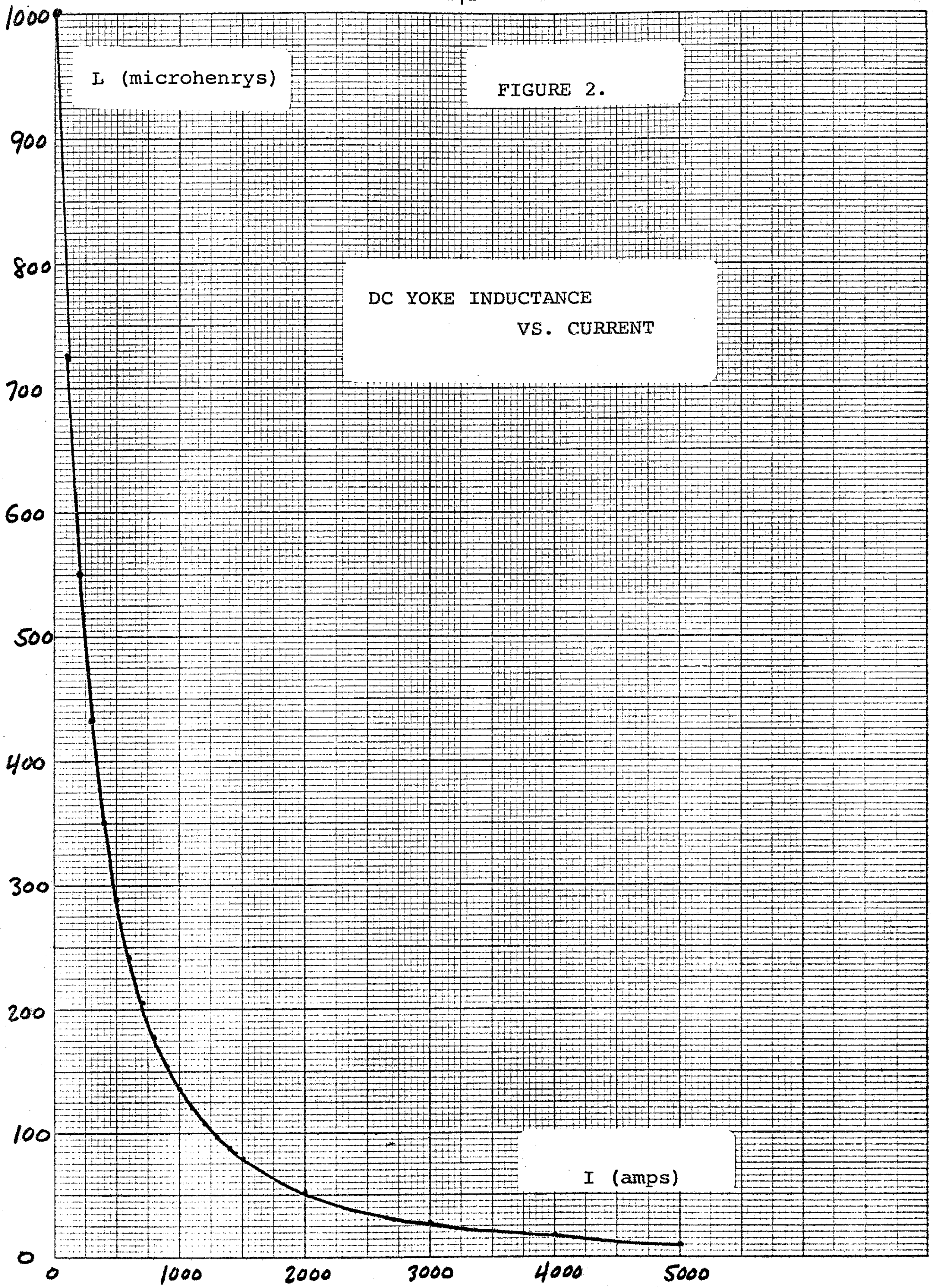
[1] R. Shafer, On the Inductance of the Doubler Magnet System, Fermilab UPC Number 126, April 2, 1980.

FIGURE 1.

$B = \mu H$

$\mu = \frac{\alpha + H}{\beta + H}$; $\alpha = 21{,}500$ $\beta = 10$




L (microhenrys)
FIGURE 2.
DC YOKE INDUCTANCE
VS. CURRENT
I (amps)
1000
900
800
700
600
500
400
300
200
100
0
0
1000
2000
3000
4000
5000

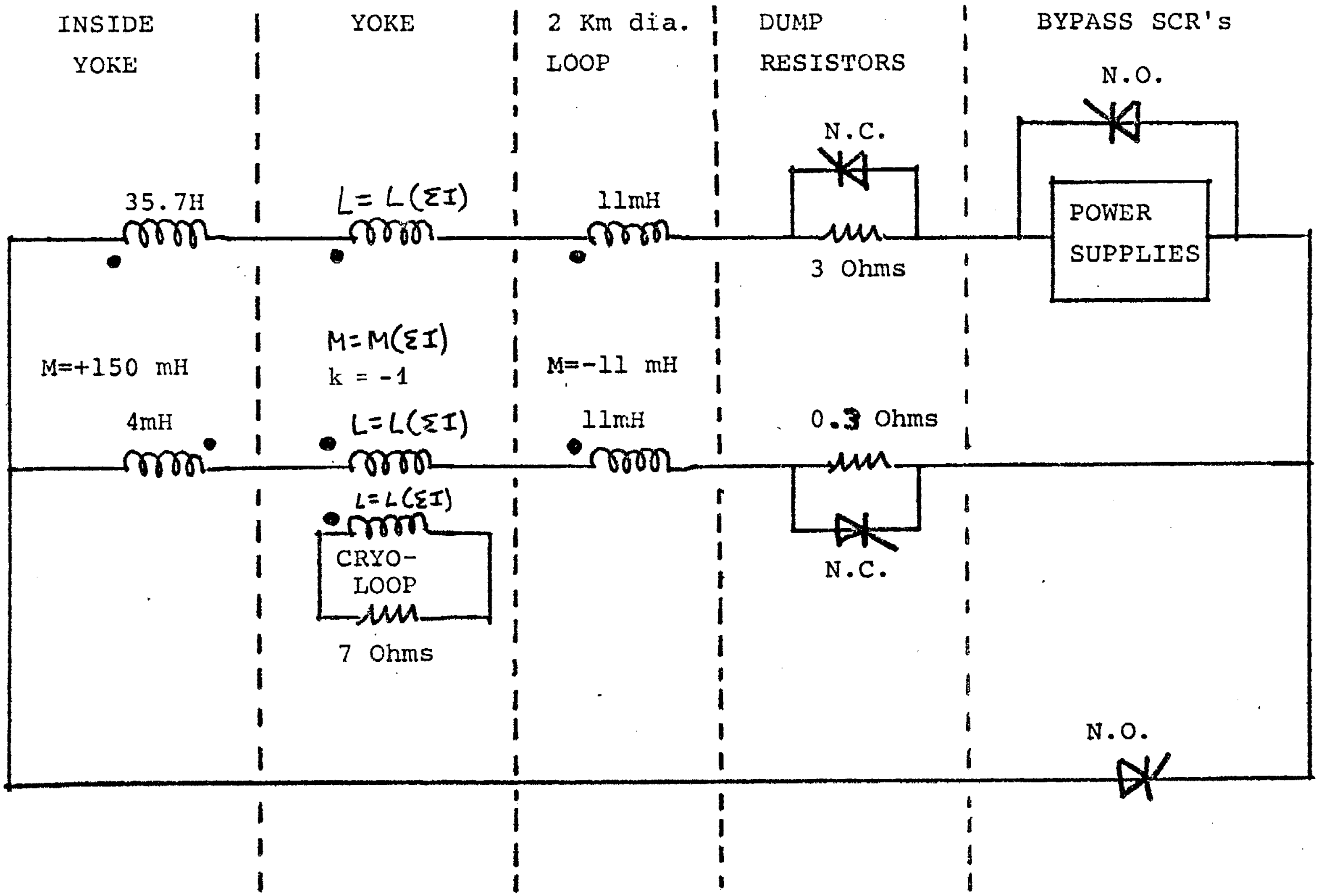
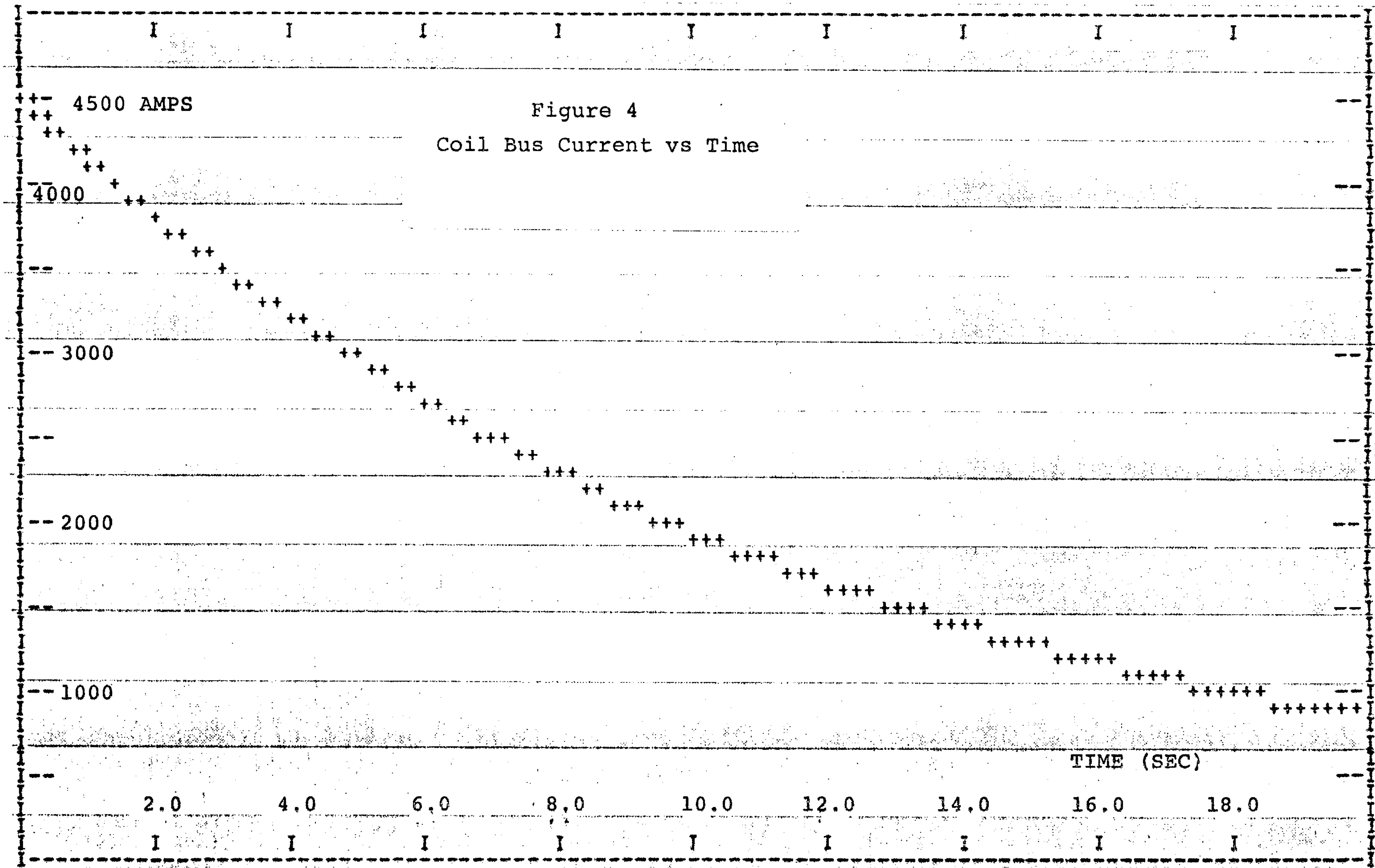


Figure 3. Equivalent circuit for nonlinear analysis of magnet system. Dots show mutual inductance polarity. For SCR's, N.O. and N.C. mean normally open and closed respectively. The yoke self and mutual inductance depends on the total current linking yoke (see text), and varies from 800 mH at zero net current to about 10 mH at 4500 amps.

Figure 4

Coil Bus Current vs Time



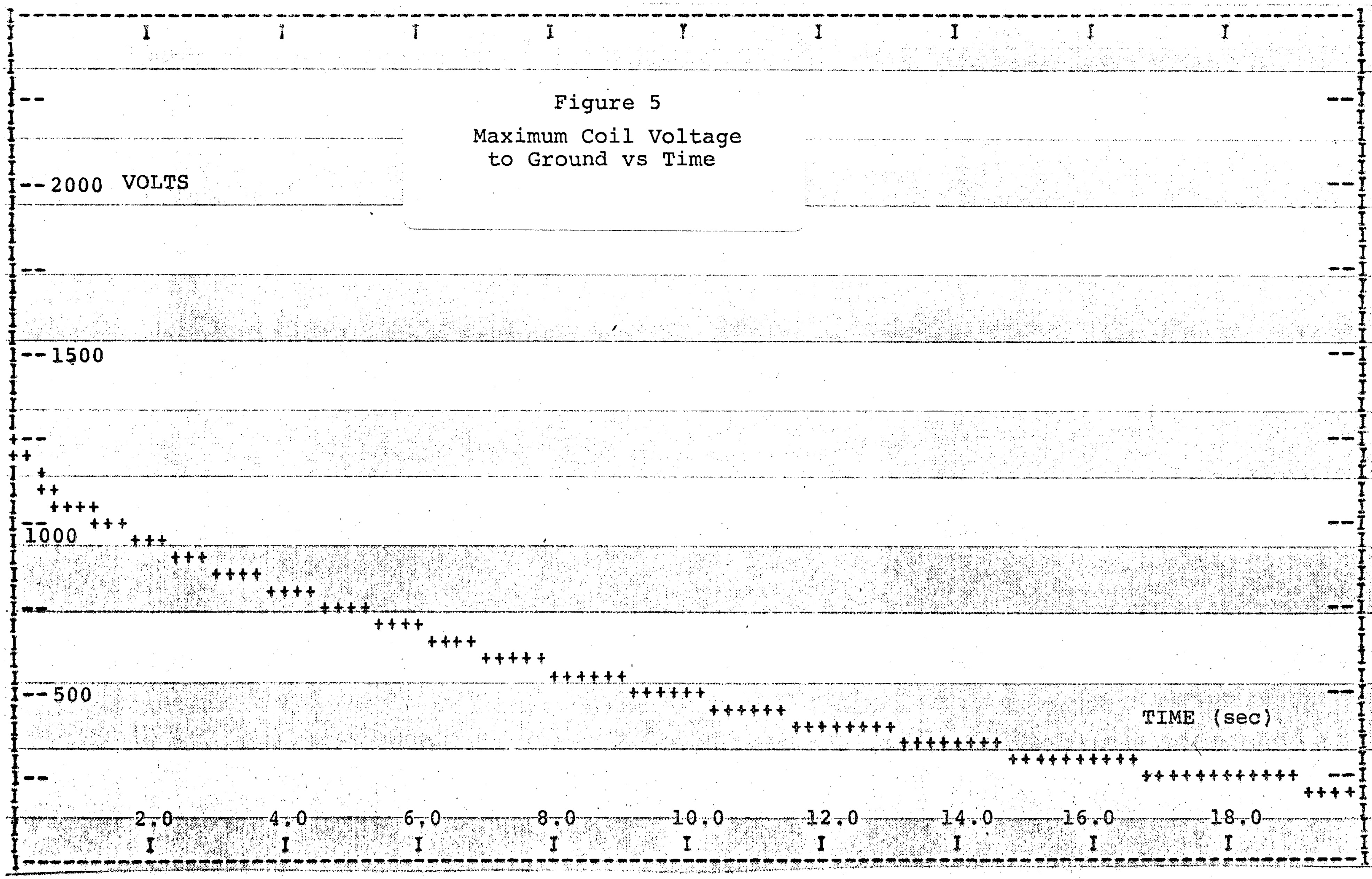


Figure 5
Maximum Coil Voltage
to Ground vs Time

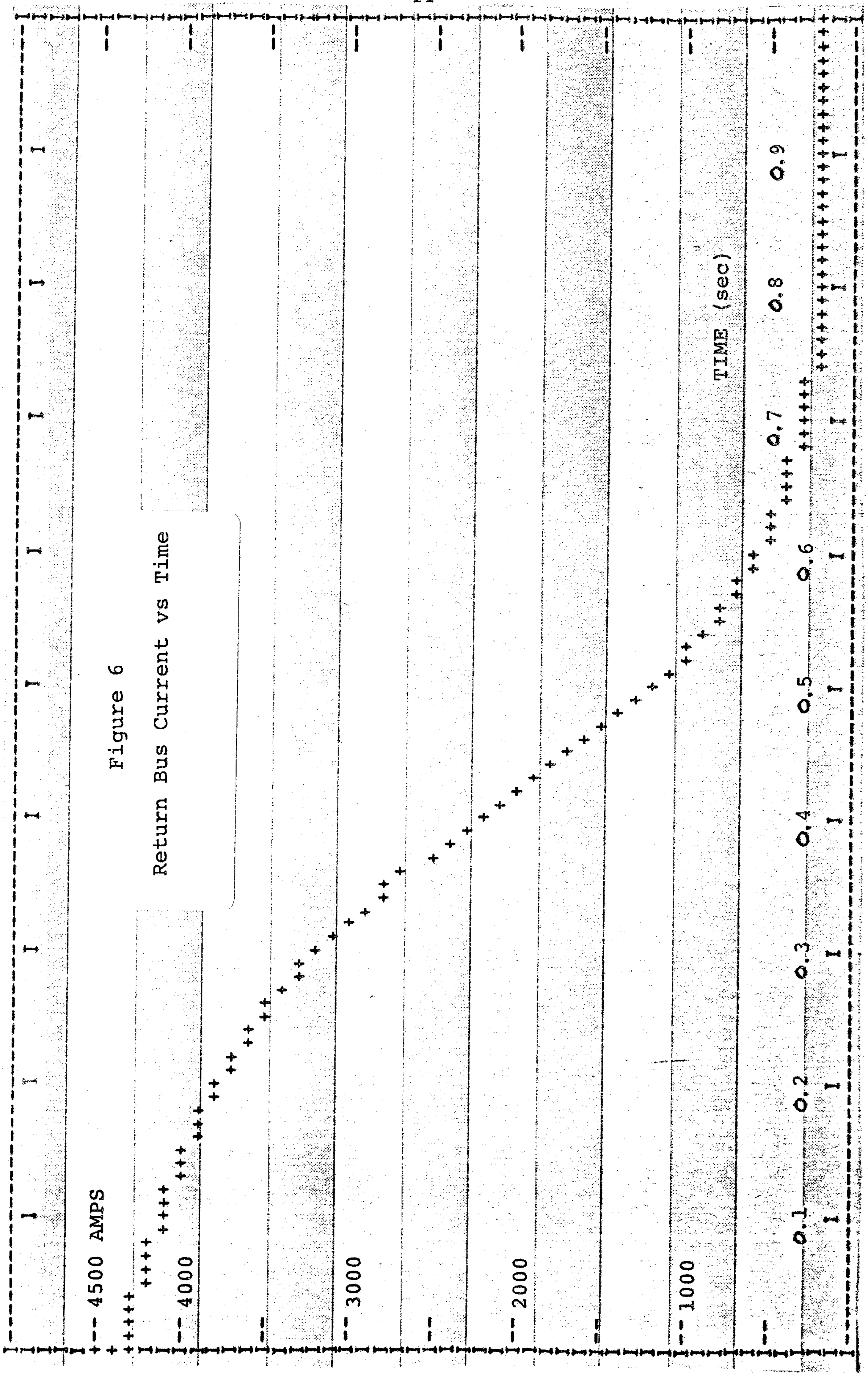


Figure 6

Return Bus Current vs Time

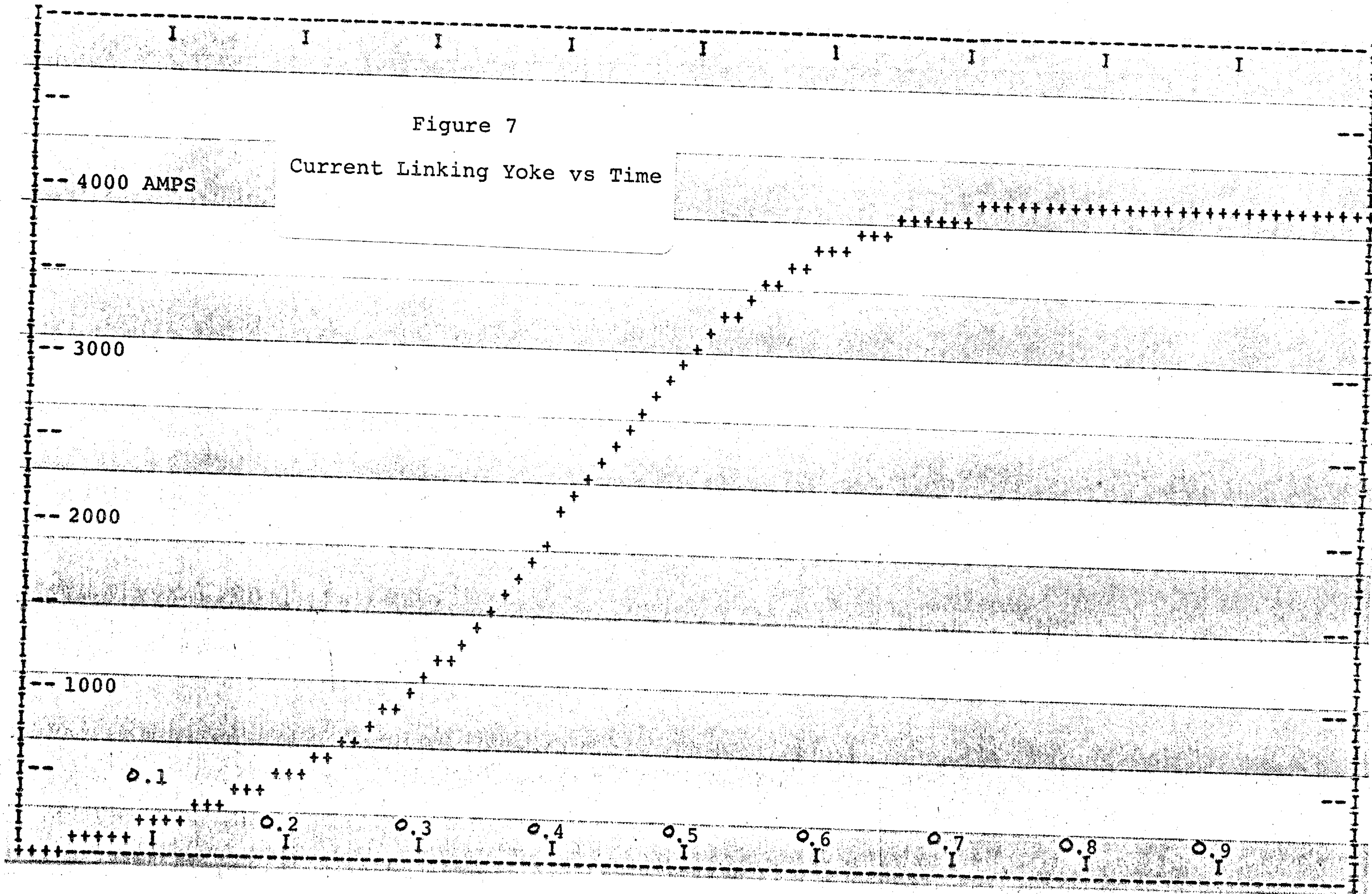


Figure 7

Current Linking Yoke vs Time

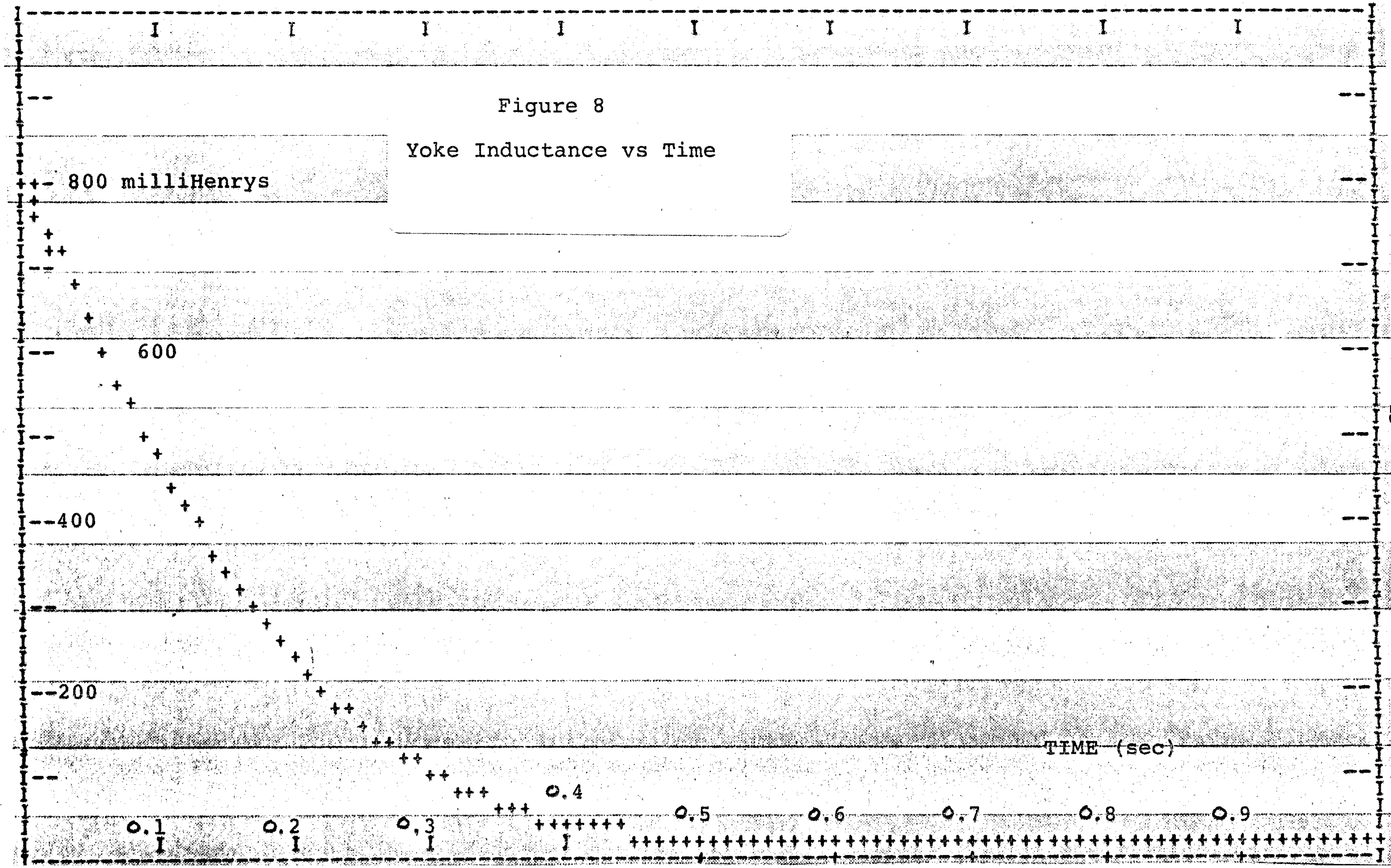


Figure 8
Yoke Inductance vs Time
800 milliHenrys
600
400
200
TIME (sec)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

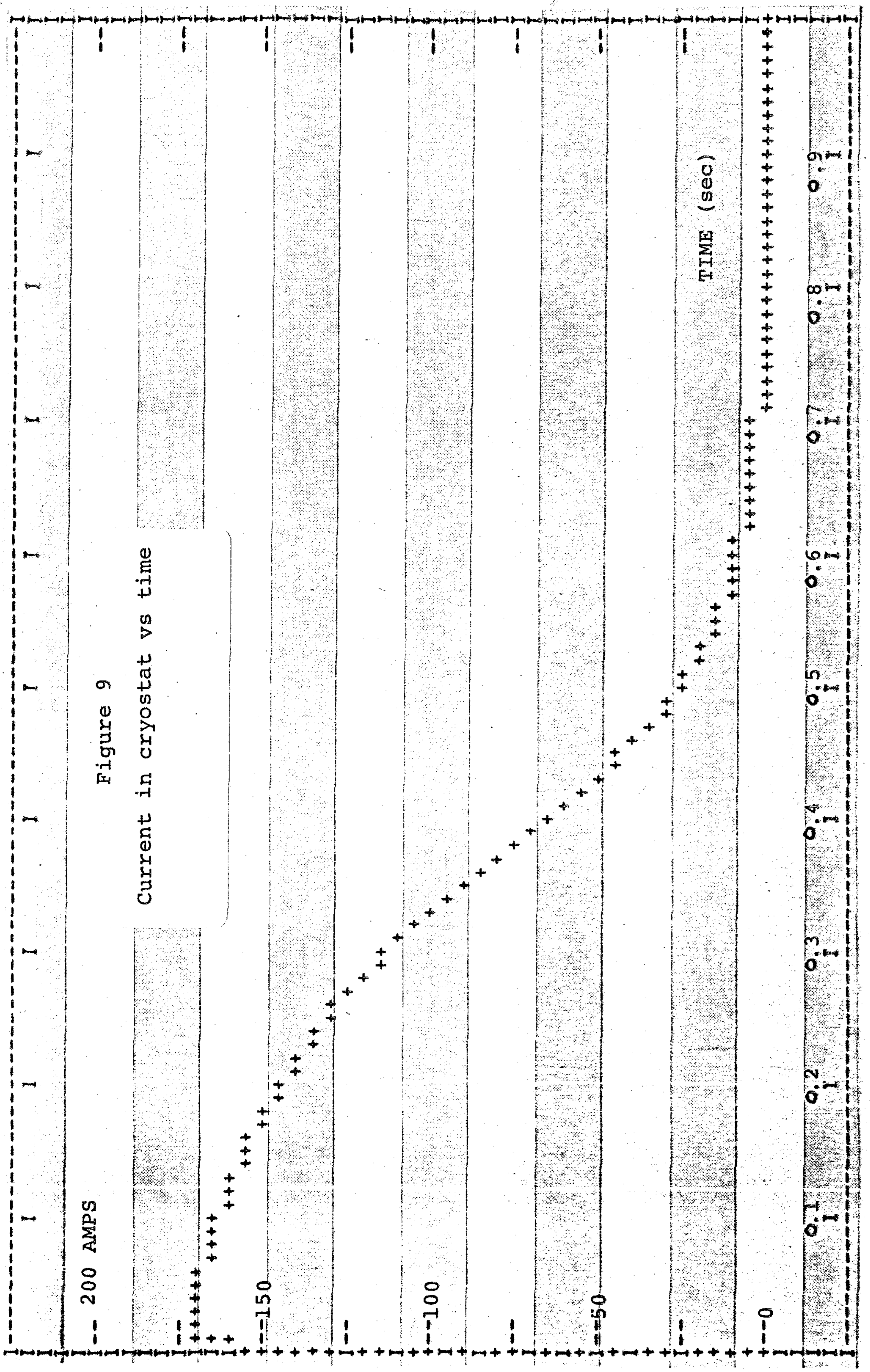


Figure 9
Current in cryostat vs time

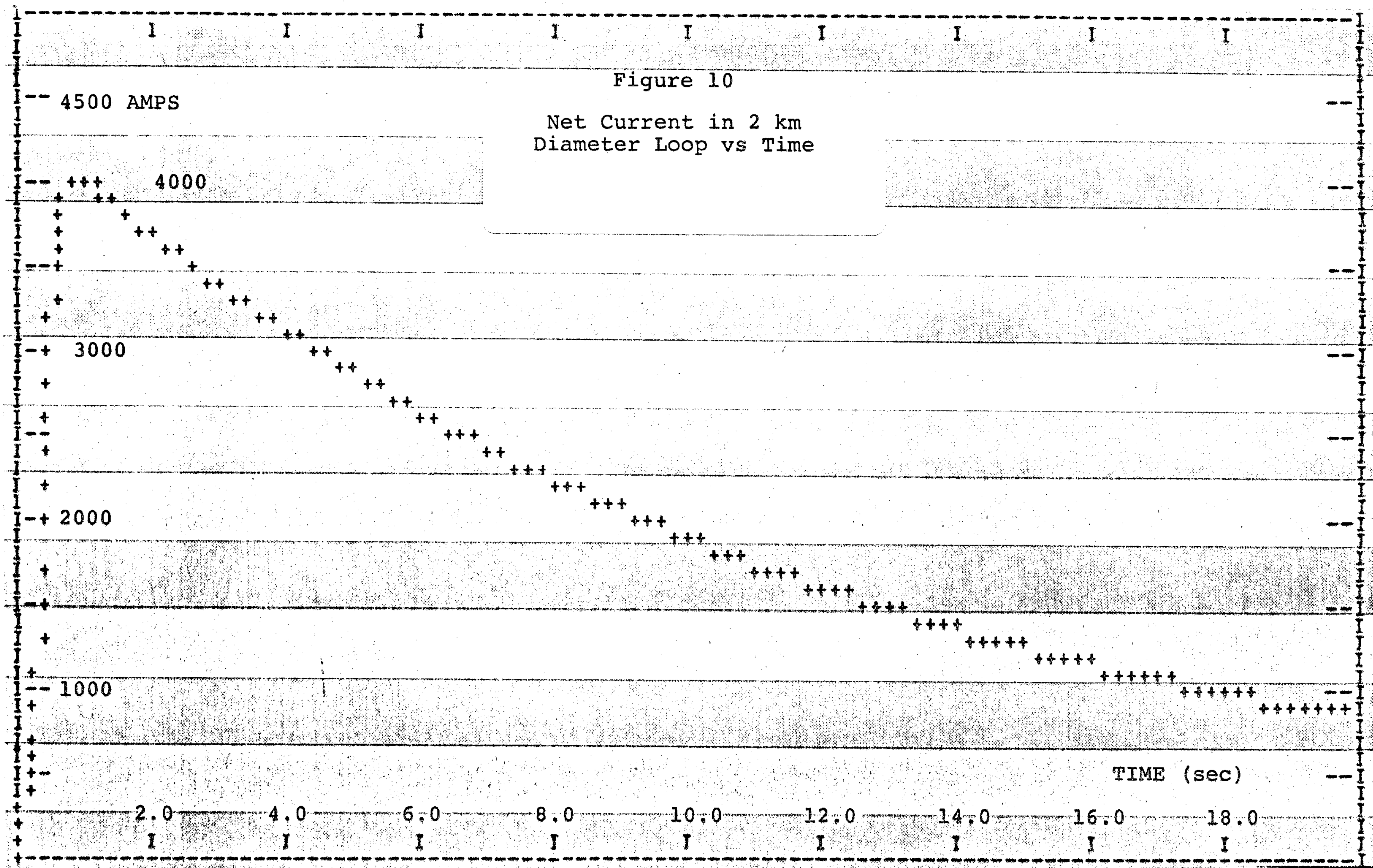


Figure 10

Net Current in 2 km Diameter Loop vs Time

Figure 11

Integrated Power (MIITs) in Return Bus vs Time