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Flowing Water NMR Measurements in the LEP Dipole

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The determination of the precise value of particle momentum is of utmost importance for the physics experiments being carried out in LEP (Large Electron-Positron Collider). One of the parameters for this exercise is obtained by measuring the magnetic field in a reference dipole connected in series with the bending magnets of the machine. The field is also measured in two bending magnets in the machine tunnel. Measurement equipment based on NMR (Nuclear Magnetic Resonance) is used. It has, however, the disadvantage of being sensitive to ionizing radiation. Also its limited measurement range causes a problem in these low field magnets. For these reasons, a system based on NMR measurements in flowing water was evaluated. The measurement method is described and results in the range from a remanent field of 0.5 mT up to the maximum field of 112.5 mT are presented. A resolution of 0.0001 mT was obtained.

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CONTENTS

1. Introduction

The determination of the precise value of particle momentum is of utmost importance for the physics experiments being carried out in LEP (Large Electron-Positron Collider) [1]. One of the parameters for this exercise is obtained by measuring the magnetic field (in the range of 0.045 to 0.12 T) in a reference dipole connected in series with the bending magnets of the machine [2]. This reference magnet is calibrated periodically by a direct measurement of flux variations in the so-called flux-loop which is a one turn induction coil embedded in the lower pole of all bending magnets installed in the machine [3]. As the requirements for measurement resolution were increased, equipment for NMR (nuclear magnetic resonance) measurements was added to the reference magnet. As an absolute standard for calibration, this method provides an ideal tool for precise measurements. Commercially available instruments measure fields in the range from 0.045 T with an accuracy better than 10 ppm. The system was later completed with the installation of two NMR systems in bending magnets in the machine tunnel.

The disadvantage of the present system is its sensitivity to ionizing radiation. Also its limited measurement range causes a problem in these low field magnets. It should be noted that the Z bosons are produced at beam energies around 45 GeV, where the bending field is about 0.05 T.

For these reasons it was suggested to evaluate a system based on NMR measurements in flowing water. The measurement equipment described in this note was developed at the Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava. It fills the gap in the measurement range up to 0.045 T, for which NMR equipment is not yet commercially available. In addition, it provides a method of measurement in environments of ionizing radiation as in particle accelerators.

2. Principle of operation of the NMR using flowing water

Nuclear Magnetic Resonance (NMR) in flowing water was observed for the first time in 1951 by Suryan [4]. Later, Sherman [5] and Zhernovoy [6] found a method to measure magnetic field using this effect. The precise NMR magnetometer using flowing water developed by Pendlebury et al. [7] has reached the precision of 10^{-7} when measuring a magnetic field of 1.8 mT. Simonov et al. [8] developed the wide range NMR magnetometer in flowing water and arrived at the precision of 3.10^{-5} in the range of magnetic field 0.05-10 T. Using a frequency synthesizer with extremely high stability and frequency step 0.01 Hz, Sheng [9] achieved an accuracy of the order of 10^{-8} measuring a magnetic field of 8.445 T in the superconducting NMR spectrometer. A magnetometer using NMR in flowing water was developed in the Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava in 1981. Since then it has been used for Hall probe calibration.

A similar system was constructed and used for the measurements described in this paper. The operation of the NMR magnetometer using flowing water, shown in Fig. 1, is explained as follows:

The water flows from the tap, through a plastic tube, to the polarizer volume Vp, where it is polarized by the field of the permanent magnet PM (0.7 T). To obtain a magnetization of the water of about 90%, it must stay in the polarizer volume (50 ccm) for a minimum of 6 seconds (3 x T1 - where T1 is the relaxation time of the normal water = 2 s). This condition corresponds to a water flow rate of about 8 ccm/s. The water then flows to the measurement probe MP, which is placed in the magnetic field to be measured, B_o. This probe consists of a glass tube with a single layer coil (40 turns). The number of the turns is not critical, it can vary from 5 to 100 depending on the homogeneity of the measured magnetic field B_o. The probe coil is connected to the output of an RF generator FG, the frequency of which is measured by the frequency-meter FM. The range of its output frequency is related to the measured magnetic field. For low magnetic fields, e.g. the Earth magnetic field, an audio generator can be used. Finally, the water goes through the analyzer probe AP, which detects the nuclear spin magnetization change when the frequency of the generator FG is:

$$f = K \, . \, B_o \qquad (1)$$

where K = 42.575857 MHz/T, is a constant derived from the gyro magnetic ratio of the protons in H_2O.

The analyzer AD consists of a marginal oscillator with detector, feedback loop and amplifier. The oscillator coil AP is wound onto a glass tube inserted in the water flow coming from the probe MP and is placed in the permanent magnetic field of the polarizer AM. This field is modulated by the twin coils MC, which are excited from the sweep generator SG with a saw-tooth current at a frequency of about 15-30 Hz. The analyzer output provides a signal proportional to the polarization of the water (the Z component of the magnetization vector) and a signal proportional to the modulating field. These signals are connected to the Y and X inputs of an oscilloscope OSC.

Even if, in the probe MP, the NMR conditions are not fulfilled, one can observe the signal of NMR absorption on the oscilloscope screen. The amplitude of this signal depends on the water flow rate. At zero water flow the signal disappears after a few seconds. These conditions must be achieved by proper adjustment of the marginal oscillator level as well as by the feedback parameter. When the frequency of the generator FG connected to the probe AP (placed in the magnetic field to be measured) is approaching the resonance frequency, the amplitude of the signal on the oscilloscope diminishes, passes through zero, then increases and reaches a maximum inverted signal. It then diminishes again, passes through zero and finally reaches the maximum value as before, out of the resonance. There are two ways to establish the resonance frequency which corresponds to the maximum inverted signal. The mean frequency of the two zero-crossings gives the exact resonance frequency and using Eq. 1 the unknown measured magnetic field can be calculated. When the signal/noise ratio is relatively small, instead of measuring the zero-crossing frequencies, one can determine the frequencies where the amplitude of the signal is one half of the maxima. For our measurements we used both methods with results as shown in Table 1.

3. Measurement results

The full excitation curve of the LEP dipole was measured in order to prove the feasibility of this method. The measurements were carried out with standard laboratory instruments. A resolution of 0.0001 mT was reached in the range from the remanent field of 0.5 mT, up to the maximum field of 112.5 mT and a corresponding reproducibility was observed. The results of the measurements are shown in Table 1 and Fig. 2. A blow-up of the hysteresis curve,

$$\Delta B = B - B_{rem} - k * I$$

where $k = 0.0241455$ T/kA and B_{rem} is the remanent field of the dipole shown in Fig. 3.

In practice, the zero-crossing measurement, described above, was slightly more difficult to perform than the half-level method, due to the rather low signal to noise ratio of the detector output. This was perhaps due to the field gradient which exists in the magnet.

4. Concluding remarks

The remarkable sensitivity and resolution of this measurement method makes it very suitable for absolute measurements at low fields. In fact, it was even possible to detect the Earth magnetic field outside the magnet, corresponding to an excitation frequency of about 2 kHz. We therefore consider the method as a possible solution to some measurement problems in the LEP tunnel. However, if automatic operation is required, further development of the related detection equipment will be needed. It might then be possible to install this type of equipment directly in the accelerator dipoles.

5. References:

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Dipole current (A)	Zero crossing measuring method (zc)			Half level measuring method (hl)			Difference	
	f1(kHz)	f2(kHz)	Bzc (mT)	f3(kHz)	f4(kHz)	Bhl (mT)	Bhl - Bzc (mT)	B avg (mT)
0.0	23.350	23.013	0.5445	23.424	22.945	0.5445	0.0001	0.5445
324.0	346.137	345.719	8.1250	346.262	345.654	8.1257	0.0007	8.1253
648.0	679.908	679.461	15.9641	680.027	679.363	15.9643	0.0002	15.9642
864.0	904.929	904.460	21.2490	905.042	904.352	21.2491	0.0001	21.2490
1404.0	1469.692	1469.275	34.5145	1469.826	1469.177	34.5149	0.0004	34.5147
1944.0	2032.342	2031.979	47.7303	2032.476	2031.837	47.7302	-0.0001	47.7303
2916.0	3038.788	3038.389	71.3688	3038.918	3038.327	71.3696	0.0008	71.3692
3780.0	3925.648	3925.217	92.1985	3925.763	3925.179	92.1994	0.0009	92.1990
4644.0	4797.601	4797.132	112.6781	4797.700	4797.011	112.6778	-0.0003	112.6779
3780.0	3964.790	3964.337	93.1176	3964.903	3964.242	93.1178	0.0002	93.1177
2916.0	3076.245	3075.785	72.2478	3076.359	3075.687	72.2480	0.0002	72.2479
1944.0	2064.825	2064.364	48.4921	2064.951	2064.261	48.4924	0.0003	48.4923
1404.0	1499.208	1498.728	35.2070	1499.325	1498.629	35.2072	0.0002	35.2071
864.0	931.890	931.394	21.8819	932.009	931.299	21.8822	0.0003	21.8821
648.0	704.901	704.431	16.5508	705.057	704.356	16.5518	0.0010	16.5513
324.0	364.579	364.145	8.5579	364.710	364.073	8.5586	0.0007	8.5583
0.0	23.404	23.093	0.5460	23.497	23.172	0.5481	0.0020	0.5471

LEP dipole measurements with the flowing water NMR

Table 1

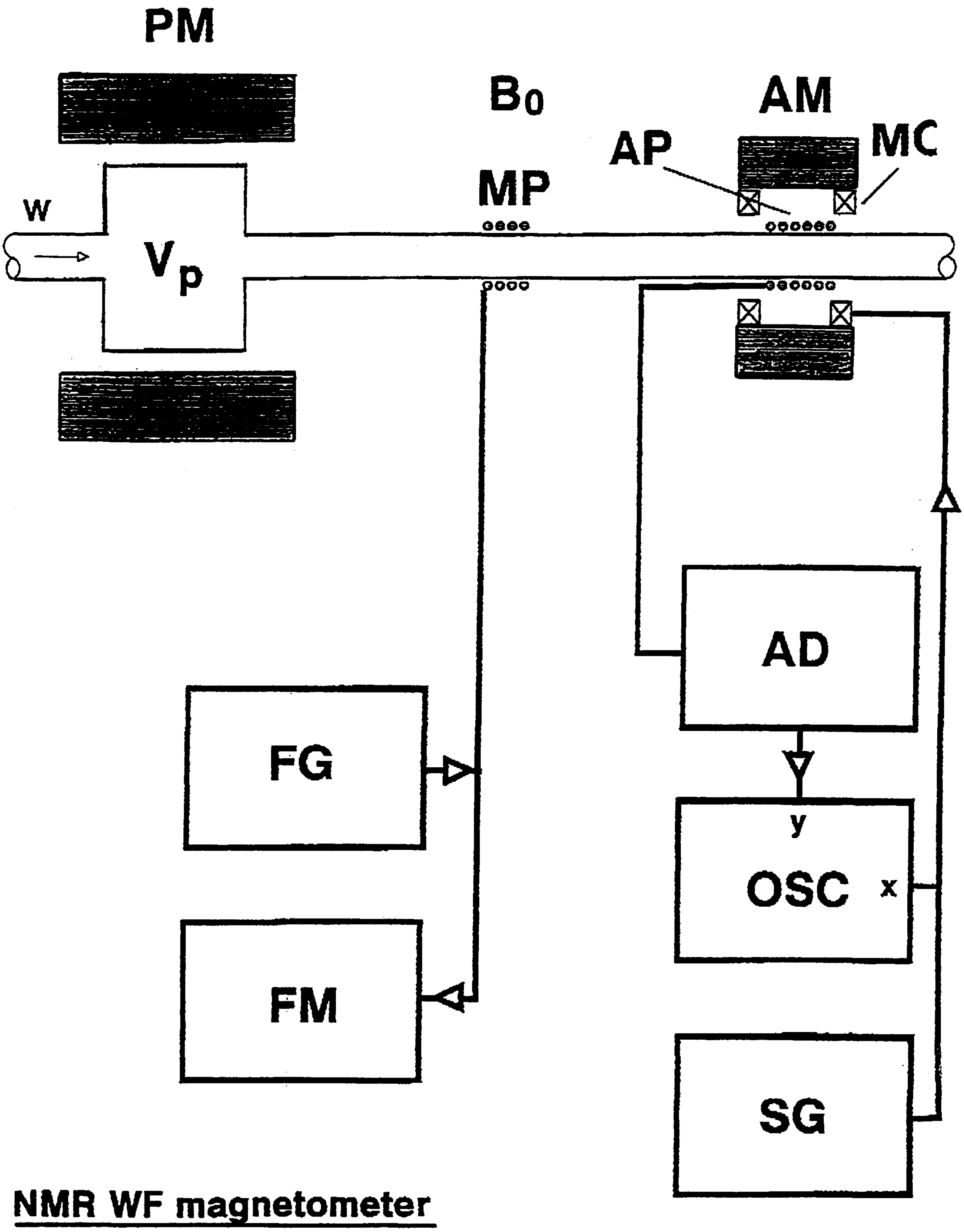

Figure 1

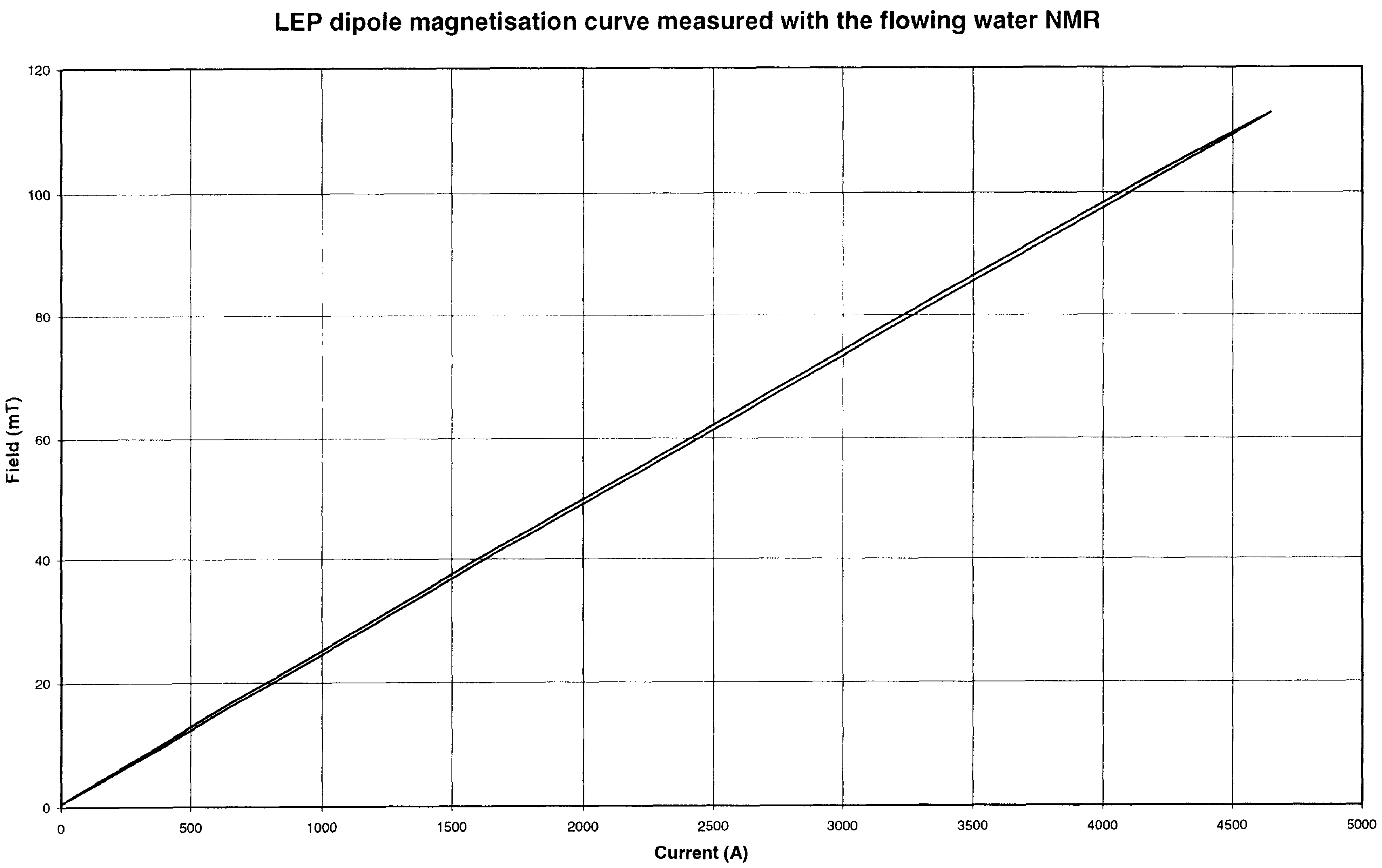
LEP dipole magnetisation curve measured with the flowing water NMR
Field (mT)
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Current (A)

Figure 2

LEP dipole hysteresis measured with the flowing water NMR

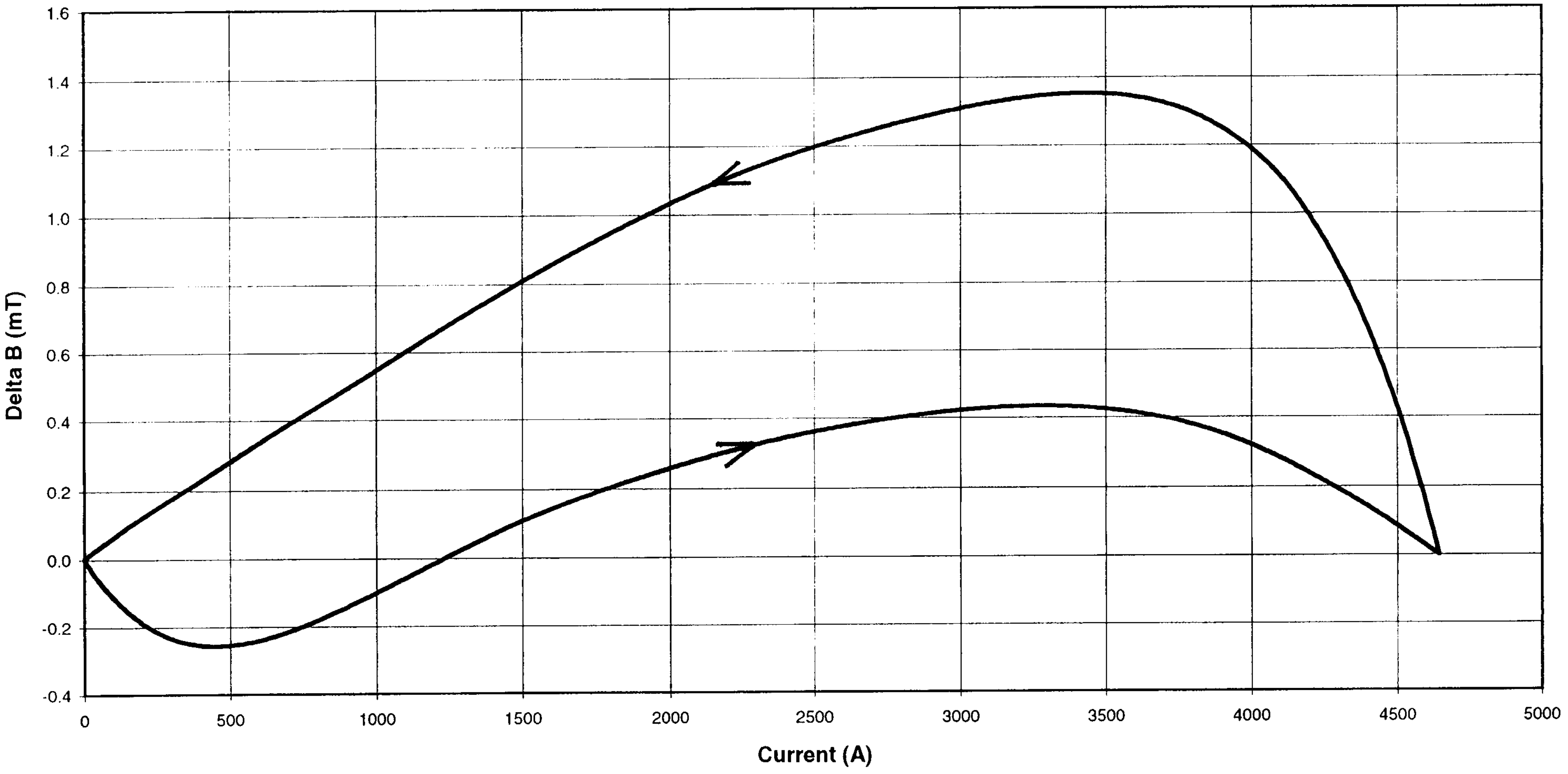

Figure 3