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MAGNETIC PERMEABILITY MEASUREMENTS

Automatic Testing of Ring Samples at Cryogenic and Ambient Temperatures

by

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Abstract

The report describes a computer-controlled system for the automatic measurement of permeability of ring samples at ambient and cryogenic temperatures. For measurements at cryogenic temperature, toroidal coils are wound directly onto the sample: the success of this method is evaluated. A correction for errors due to the radial distribution of flux density in the ring sample is discussed.

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CONTENTS

1. INTRODUCTION

The use of ring samples for the determination of permeability by the ballistic method has been standard practice at the CERN Intersecting Storage Rings (ISR) Division for some years. Measurements have been previously performed at ambient temperature in a split-coil permeameter with a semi-automatic system[1]. The present report describes a computer-controlled system in which measurements are performed at ambient temperature using a split-coil permeameter and at cryogenic temperatures using wound-toroids where the flux-measuring and excitation coils are wound directly onto the sample. Two fairly distinct points are of interest, namely the evaluation of the computer-controlled system when used in conjunction with the well-proven split-coil permeameter and the evaluation of the wound-toroid as a measurement device. In addition, a programmed correction for errors due to the radial distribution of flux density in the ring sample is discussed and evaluated.

2. DESCRIPTION OF THE INSTALLATION

The layout of the measuring system is shown in Fig. 1. Two power supplies are used to cover the working range of current. The supplies are current-regulated and are commanded by the computer through a 16-bit digital-to-analog converter (DAC) as voltage reference source.

The integrator is based on a low-drift chopper-stabilized operational amplifier and employs a Teflon capacitor for high leakage resistance and low dielectric absorption. The reading of integrated voltage is performed by the computer via a 14-bit analog-to-digital converter (ADC).

A suite of interactive programs provides for calibration of the power supplies and of the ADC, demagnetization, measurement of permeability at field values defined by the operator or an automatic traverse of the complete range at internally generated field values, and measurement of coercivity. Measured data are listed on a line-printer and/or CRT and where appropriate, stored on data files as a record or for subsequent graphical display.

The split-coil permeameter has a 180 turn excitation winding and a 90 turn flux measurement winding. Maximum excitation current is limited to 40 A to avoid overheating the instrument so that the maximum magnetizing field in a measurement at ambient temperature is 24'000 A/m. The integrator time constant is set to give maximum integrated voltage with this field level and a 90 turn measurement winding.

While the above construction facilitates the exchange of samples, the resistance of the excitation coil is inherently high due to the contact resistances (two per turn) so that even at liquid helium temperature power dissipation would seriously limit the fields attainable. Thus, for measurements on solid samples at cryo-

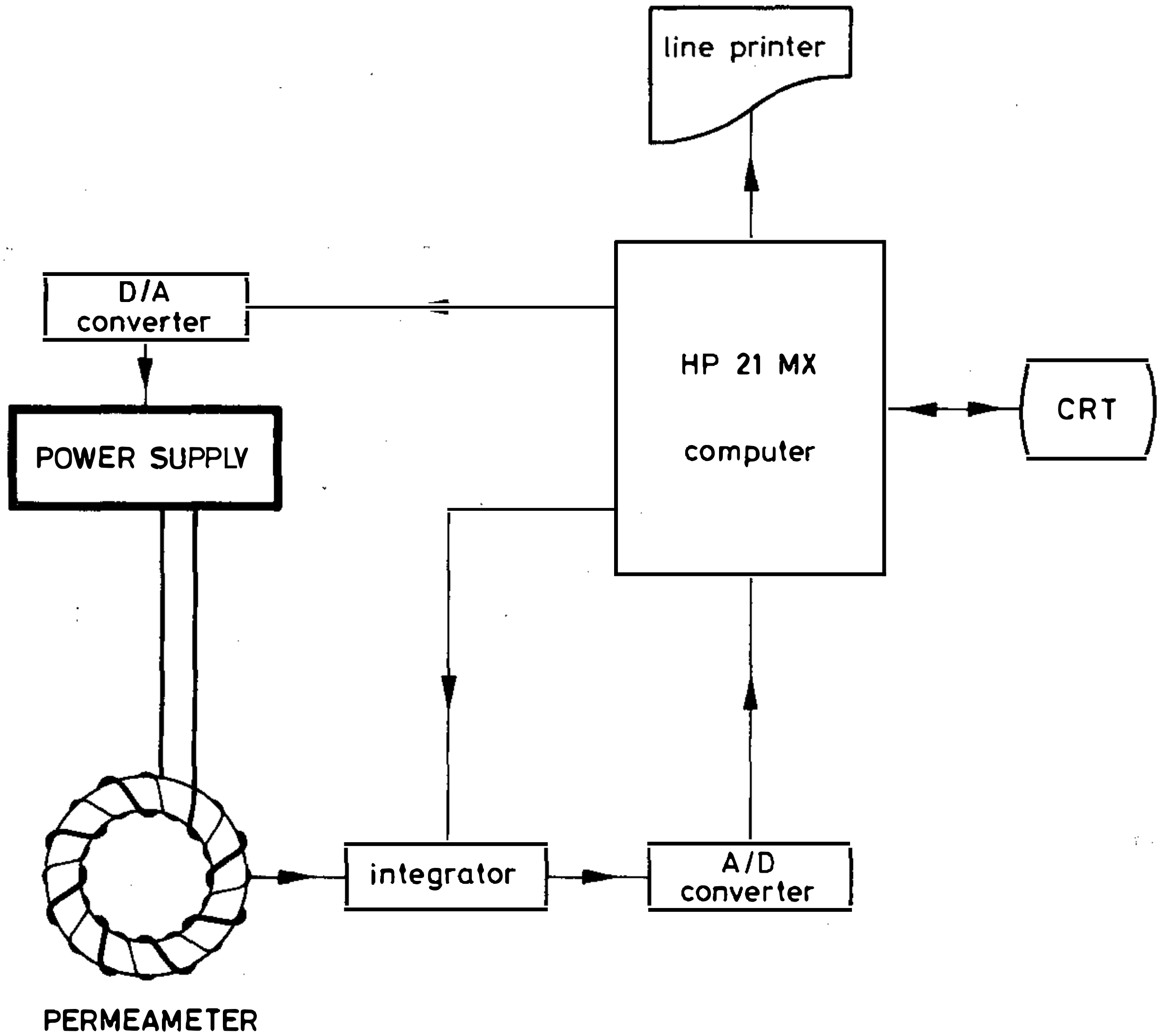

Fig. 1 Layout of the measuring system

genic temperatures, the measuring coil and excitation coil are wound directly onto the sample using a toroidal-winding machine and enamel-insulated copper wires of diameters 0.2 mm and 1.0 mm, respectively. The wound-toroids required for a complete measurement at liquid helium temperature have been approximately standardized at 180 excitation / 90 sense turns and 2500 excitation / 55 sense turns. The maximum achievable field at liquid helium temperature is of the order of 800'000 A/m.

3. THE AUTOMATIC MEASURING SYSTEM

3.1 Demagnetization

Demagnetization is commenced at a magnetizing field sufficient to bring the sample into saturation (typically 6000 A/m). The current is decreased in steps according to a geometric progression so that the decrements in H become very small at lower fields along the steep portion of the B - H curve where the process is most sensitive. A demagnetization from 6000 A/m to 10 A/m is made in about 100 steps: measurements begin at 20 A/m.

3.2 Permeability measurement

For a sample subjected to an excitation of I amperes in N turns, the magnetizing field H at radius r in the sample is defined as $H = NI/2\pi r$. For a sample of internal radius r_i and external radius r_e, the average magnetizing field $\overline{H}$ is

$$\overline{H} = \frac{1}{r_e - r_i} \int_{r_i}^{r_e} \frac{NI}{2\pi r} \, dr = \frac{NI}{2\pi r_0} ,$$

where:

$$r_0 = \frac{r_e - r_i}{\ell n \; r_e / r_i} .$$

The flux established within the sample at excitation current I is obtained from the integral of the voltage induced in the measuring coil during reversal of I: the average flux density B_{av} is defined as this value of flux divided by the sample cross-sectional area. The permeability of the sample is initially defined as $B_{av}/\overline{H}$ and is subsequently corrected for the effect of the radial distribution of flux density (Chapter 5).

At low fields, successive reversals of the magnetizing field are required to condition (bring into a cyclic state) the sample before measurement. The use of six premeasurement reversals in the range 0 - 5000 A/m and three reversals in the range 5000 - 15000 A/m has been found sufficient to eliminate the effect within the resolution of the measurement.

The current is raised on a software generated ramp rather than in a single step to avoid overshoot and to minimize generation of eddy currents. In the case of a measurement at high fields, the integrator is read as soon as the ramp terminates while at low fields, it is necessary to await the decay of eddy currents. The measurement cycle varies from 7 s at low field to 2.5 s at high fields.

In order to monitor and eventually compensate the effect of integrator drift upon the measurement, readings of integrated voltage are taken for two consecutive reversals. The average of the difference of the two readings is used to calculate the flux density: the average of the sum contains the effect of integrator drift and is recorded and in the case of a high drift may be used to warn the operator of a malfunction.

3.3 Characteristics of the individual components

At present, the power supplies have different accuracies so that the magnetizing field is known with an accuracy of 0.4 ^{o}/oo at field levels above 6128 A/m, with an accuracy of 0.5 ^{o}/oo from 6128 to 200 A/m and with a decreasing accuracy thereafter reaching 5 ^{o}/oo at 20 A/m. The effect of the DAC, which has a maximum error of 0.15 ^{o}/oo, is included in these figures.

Attention was paid to the level of current ripple acceptable in the measurement. The effect of current ripple is to modulate the d.c. magnetizing field, producing a variation of flux density along a minor hysteresis loop. As the slope of a minor hysteresis loop is always less than the slope of the magnetization curve at a given field level, a pessimistic assessment of the effect upon the measurement is obtained by assuming that the consequent variation of flux density follows the magnetization curve. On this basis and from measurements using a source with various imposed levels of ripple, it was found that the modulation of flux density would be less than 1 ^{o}/oo if the peak-peak current ripple were not to exceed 1 ^{o}/oo of d.c. for a measurement at low fields (around 160 A/m) and 1 % of d.c. for a measurement at high fields (above 6000 A/m). At present, the high field specification is met but the peak-peak ripple upon the low field measurement is up to 5 ^{o}/oo. (A suitable low current supply with 1 ^{o}/oo peak-peak ripple and 0.4 ^{o}/oo accuracy is in preparation.)

The integrator time constant is measured with an error of 0.3 ^{o}/oo. The maximum error on the reading of integrated voltage by the analog-to-digital converter corresponds to 0.0005 T in the range 0 - 2 T and 0.001 T in the range 2 - 3 T.

3.4 System performance

The performance of the system was assessed from measurements in the split-coil permeameter. For a given sample of low carbon steel, the dispersion upon six measurements was not greater than $\pm 6 \times 10^{-4}$ T at flux densities above 1 T (i.e. a maximum of 0.6 ^{o}/oo): at flux densities down to 0.4 T, the dispersion was less than ± 3 ^{o}/oo and at lower flux densities was a maximum of ± 2 %.

The dispersion upon the measurement above 1 T is mainly accounted for by the ADC with a minor contribution from the power supply. The flux density of 0.4 T occurs for the above steel at about 150 A/m where the slope of the B - H curve is of the order of 0.005 T per A/m: the power supply error at this level is about ± 0.7 ‰ and can thus contribute an error on the flux density of the same order as that due to the ADC, i.e. ± 0.0005 T, 1.3 ‰. At low flux densities, the ADC error again predominates.

4. WOUND TOROIDS

4.1 General

Measurements at cryogenic temperatures are performed in liquid helium and liquid nitrogen. The current leads are constructed from thin copper sheet and have a cross-sectional area of 4 mm^2. The cryostat used for the liquid helium measurement is a commercial apparatus of 250 mm internal diameter. The rate of evaporation of liquid helium measured in steady-state conditions without current is 6 ℓ/min: this corresponds to a heat-inleak of 0.4 W, a value which compares well with that obtainable with gas-cooled leads of 200 A capacity.

4.2 Reproducibility

The reproducibility of the measurement of flux density was tested using one sample of low carbon steel wound six times with a 180 excitation / 90 sense turns combination and wound four times with a 2500 excitation / 55 sense turns combination. The sample was measured at ambient temperature, to allow comparison with results for the same sample measured in the split-coil permeameter, and at liquid nitrogen temperature. The results are summarized as follows:

a) 180/90 turns, ambient:

In the range 1.5 - 2.0 T, the maximum dispersion is ± 0.8 ‰. From 1.0 - 1.5 T, the maximum dispersion is ± 3.0 ‰ and below 1 T, the maximum dispersion is ± 2.5 %,

A comparison of the average of six measurements in the split-coil permeameter with the average of six wound-toroids shows differences of less than ± 0.6 ‰ in the range 1 - 2 T, differences of up to 1 % in the range 0.5 - 1.0 T and reaching up to 4 % at lower field levels.

b) 180/90 turns, liquid nitrogen:

The maximum dispersion is ± 0.7 ‰ in the range 1.5 - 2.0 T, ± 3 ‰ in the range 1.0 - 1.5 T and up to ± 4 % at lower fields.

c) 2500/55 turns, ambient:

In the range 1.6 - 2.0 T, the maximum dispersion was ± 0.6 $^{o}/oo$.

d) 2500/55 turns, liquid nitrogen:

In the range 1.6 - 2.8 T, the maximum dispersion was ± 0.8 $^{o}/oo$ occurring in the region of 2.8 T.

For the small coils, the reproducibility of the results above 1.5 T does not differ greatly from that obtained in the split-coil permeameter. The higher dispersion on results below 1.5 T is introduced by two rather asymmetric windings: it seems likely that the effect of asymmetry is to hinder demagnetization as 1.5 T is the flux density level at which the effect of non-demagnetization disappears. Although the results in liquid nitrogen show a slightly higher dispersion, no obvious explanation was found. At low fields in liquid nitrogen, systematic differences of the order of 2 % are found depending upon whether the sample was demagnetized at ambient or at liquid nitrogen temperature (the effect disappears at 1.5 T).

The higher dispersion on results with the large coils at the highest field in liquid nitrogen is assumed to be due to asymmetry. These coils comprise about ten layers and it is difficult to avoid asymmetries in the last layers: it is possible that the windings could be improved if a filler-material were used.

4.3 Correction for leakage flux

The measured flux density requires correction to take account of the leakage flux which is external to the sample but links the measuring coil due to its finite diameter.

In the first instance, a correction was obtained by calculations assuming that the measuring coil was tightly wound so as to be everywhere in contact with the outside of the sample. When expressed in terms of an equivalent permeability, the correction is constant for a given wire diameter and is 0.028 units for a wire diameter of 0.2 mm. The influence on permeability μ would thus approach 3 $^{o}/oo$ at $\mu = 10$.

In the case of the split-coil permeameter, the leakage correction is made on the basis of a measurement of the integrated voltage during inversion at a given excitation without a sample in the permeameter[1)]. Using a brass sample, a similar measurement was performed for the wound-toroid construction. Results for a sample wound with 180 and 2500 excitation turns measured at ambient and liquid nitrogen temperatures give a leakage correction of 0.035 - 0.045 units on permeability. That the measured value is higher than the calculated value is thought to be due to the measuring coil not being everywhere in close contact with the sample surface.

5. RADIAL DISTRIBUTION OF FLUX DENSITY

5.1 General

While the distribution of magnetizing field within the sample is known analytically, varying as a hyperbolic function of sample radius, the radial distribution of flux density cannot be so simply described. The value of magnetizing field, to which the measurement is referred, is the average value $\bar{H}$ defined in Section 3.2. The value of flux density measured, B_{av}, is, by definition, the average value of the distributed flux density. In general, B_{av} will not occur at the point in the sample where $\bar{H}$ occurs, so the measured flux density requires adjustment in order to obtain $B(\bar{H})$ and allow definition of the true permeability at $\bar{H}$.

The true function B(r) which describes the radial distribution of flux density is such that

$$B_{av} = \frac{1}{r_e - r_i} \int_{r_i}^{r_e} B(r)\, dr \ .$$

If an approximation to this function is $B_a(r)$, then it will be found that

$$B_{av} - \frac{1}{r_e - r_i} \int_{r_i}^{r_e} B_a(r)\, dr = \Delta B \neq 0 \ .$$

In the ideal case, ΔB should then be distributed such that

$$\Delta B = \frac{1}{r_e - r_i} \int_{r_i}^{r_e} b(r)\, dr$$

to obtain

$$B_{av} - \frac{1}{r_e - r_i} \int_{r_i}^{r_e} \left(B_a(r) + b(r)\, dr\right) = 0.$$

5.2 Method of correction

An approximation to $B_a(r)$ is obtained by fitting a function through three adjacent measurements. For the three adjacent measurements, B_{av1}, B_{av2} and B_{av3}, corresponding to field strengths $\bar{H}_1$, $\bar{H}_2$ and $\bar{H}_3$, it is assumed as a first approximation that B_{av2} occurs at r_0 and that

$$B_a(r) = B_{av2} + (r - r_0)\, B'_a\,[r_0] + \frac{(r - r_0)^2}{2}\, B''_a\,[r_0] \ ,$$

where r_0, as defined in Section 3.2, is the radius at which the average value of magnetizing force occurs, and $B'_a[r_0]$ is the first derivative of $B_a(r)$ evaluated at r_0 and similarly for $B''_a[r_0]$.

Having assumed that B_{av2} occurs at r_0 in the sample, then B_{av1} and B_{av3} occur at equivalent radii

$$r_1 = \frac{\overline{H}_2 \, r_0}{\overline{H}_1} \quad ; \quad r_3 = \frac{\overline{H}_2 \, r_0}{\overline{H}_3}$$

and substituting these particular values in $B_a(r)$, $B'_a[r_0]$ and $B''_a[r_0]$ may be evaluated. For the automatically generated measurement series mentioned in Chapter 2, r_1 and r_3 are approximately the external and internal radii of the sample, but need not be exactly so providing the function $B_a(r)$ is integrated within the true limits r_e and r_i.

The correction factor ΔB is then applied to B_{av2} to give a better approximation to $B(\overline{H}_2)$, i.e.

$$B(\overline{H}_2) \doteqdot B_{av2} + \Delta B \ .$$

This implies that b(r) is a constant equal to ΔB and is approximately true since the correction to be applied to adjacent points should change little.

The correction is thus applied throughout the data series taking every set of three adjacent measurements sequentially. The two end points are corrected using the correction applied to their neighbours. The new data series is then corrected in the same fashion, and so on until convergence. Although the correction is made only upon the absolute value of flux density without regard to errors upon the derivatives, $B'_a[r_0]$ and $B''_a[r_0]$, these values are adjusted automatically with the creation of each new data series.

5.3 Assessment of the method

The method was assessed by application to a set of constructed data. These were obtained by defining a function $B(\overline{H})$, continuous over a certain field range, and then, for a series of discrete values of magnetizing field, evolving the value of flux density which would be obtained in a measurement. These "measured" values differed from the corresponding $B(\overline{H})$ values by up to 7 ‰. Correction of the "measured" values yielded approximations to $B(\overline{H})$ with an accuracy better than 0.8 ‰ after three iterations. It was concluded that errors due to the radial distribtuion of flux density could be expected to be reduced by a factor 5 using this correction.

5.4 Application to measured values

For sets of measured results, three iterations produce corrected values for which the differences between second and third iterations are not greater than 0.3 ‰. The difference between corrected and measured values is shown in Fig. 2

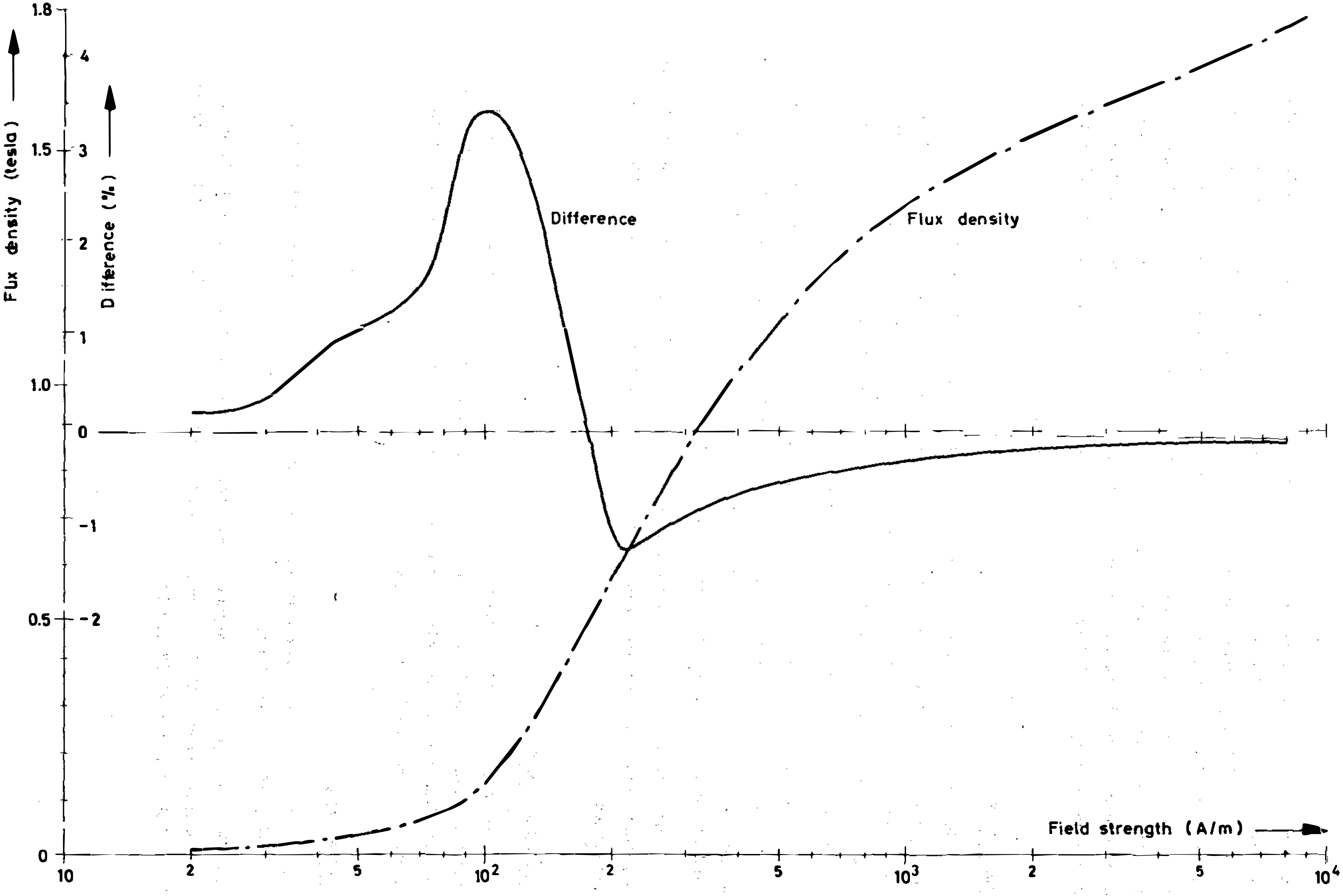

Fig. 2 Difference between measured and corrected values of flux density

with the B - H curve as background: this function represents the error made if the permeability μ is defined as $\mu = B_{av}/\bar{H}$. The error is seen to reach a maximum of about 3.5 % with high errors occurring over a rather narrow field range. Assuming a reduction of this error by 5, corrected results may be expected to contain errors due to field distribution of less than 7 ‰ at maximum in the range 30 - 300 A/m and considerably less over most of this range. Elsewhere, correction of the results should reduce the errors to the order of the measurement error. At fields in excess of 10^4 A/m, the error on uncorrected results is less than 1 ‰.

6. CONCLUSION

The computer-controlled system performs as expected. It affords a great flexibility in the measurement sequence, allowing easy adaptation to the varying requirements of precycling, pulse length, etc. The data handling facilities are particularly convenient for the processing of the measured data as in the correction of the effect of the radial distribution of flux density.

While the wound-toroid method gives a performance slightly inferior to that of the split-coil permeameter, the results are satisfactory, particularly in the range 1.5 - 3.0 T which is the more significant region for a steel which is to be used at cryogenic temperature in a superconducting magnet.

The system has been used to measure the steel used in the core of the prototype superconducting quadrupole magnet for the ISR and these results have already been published[2].

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