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MAGNETIC PERMEABILITY MEASUREMENTS AT CRYOGENIC TEMPERATURES

by

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Summary

A new low-μ permeameter based on a flux variation method has been developed for use at cryogenic temperatures and for flux densities up to 6 T. Results of permeability measurements on stainless steels and other low-μ materials are given for the temperature range 4.2 - 300 K. The instrument has also been successfully used for measurements on low-carbon steel in the extreme saturation region; their results complement those obtained at lower fields using a ring method.

1. - Introduction

Magnetic properties of materials used for the components of either "conventional" or superconducting magnets (such as iron core, coil-former cylinder, spacers, cryostat walls, vacuum chamber, supports, clamping, welded joints) have to be measured at operational temperatures and fields.

The devices described in this paper were specially designed for permeability measurements on materials used in the construction of superconducting magnets. Permeabilities can be measured in the temperature range 4 K - 300 K at inductions up to 6 T.

2. - Measurement of low permeabilities

2.1 - Principle of the low-μ permeameter

The permeability μ is determined from the value of induction B corresponding to a magnetizing force H in the material (μ = B/H) along the curve of first magnetization. The internal magnetizing force is calculated: in an open sample (e.g. rod of circular section), H is composed of the externally applied magnetizing force and the oppositely directed so-called demagnetizing field H_D due to the poles of the sample itself. Induction B in the sample is measured. In the low-μ permeameter, a cylindrical sample is surrounded at its centre by a close fitting flux measuring coil and placed in the homogeneous field region of a superconducting solenoid (see Fig. 1). At a given field, the sample is removed from the coil to a sufficient distance. During the removal, a voltage is induced in the coil and its time integral, equal to flux variation in the coil, is measured by an elec-

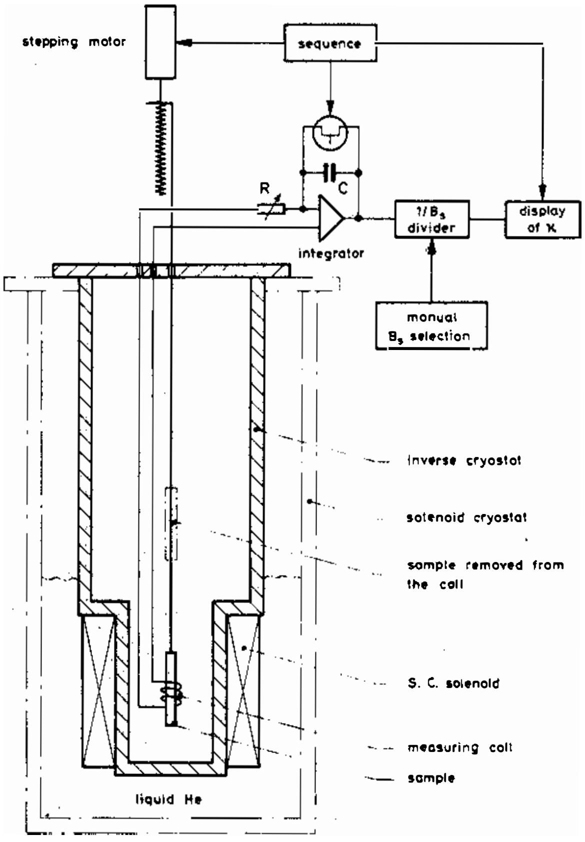

Fig. 1 Scheme of the low-μ permeameter

tronic integrator. The magnetic susceptibility of the sample, which is proportional to the flux variation, is directly displayed on a digital voltmeter.

2.2 - Theory of the measurement

The flux in the search coil consists of the flux in the sample and of the flux in the annular space between the sample and the turns of the coil. The latter is a resultant of the magnetizing force of the solenoid (H_S) and of an oppositely directed leakage field $H_\ell(r)$ from the magnetized sample. $H_\ell(r)$ and the demagnetizing field H_D can be expressed by:

$$H_\ell(r) = \frac{D(r)}{\mu_0} B_i \qquad\qquad H_D = \frac{D}{\mu_0} B_i \quad , \tag{1}$$

where D is the demagnetizing factor which depends on the sample geometry and its permeability; D(r) equals D at the surface of the sample and decreases as one moves away from the sample; B_i is the intrinsic induction in the sample ($B_i = B - \mu_0 H$).

The flux variation during the sample removal from the coil is

$$\Delta\Phi = nA(B - \mu_0 H_S) - 2\pi B_i \sum_{i=1}^{n} \int_{r_0}^{r_i} D(r) r dr \ , \tag{2}$$

A is the section area of the sample of radius r_0 and r_i is the radius of the i^{th} coil turn.

Introducing susceptibility $\kappa = B_i/\mu_0 H$ and using relations (1) and (2), the output voltage of the integrator (time constant τ) is

$$V = \kappa B_S nA \frac{1}{\tau} \frac{1 - D - D_\ell}{1 + \kappa D} \ , \tag{3}$$

where:

$$D_\ell = \frac{2\pi}{nA} \sum_{i=1}^{n} \int_{r_0}^{r_i} D(r) r dr \ ,$$

B_S is the induction produced by the solenoid in the absence of the sample ($B_S = \mu_0 H_S$).

2.3 - Choice of sample and search coil geometry

The diameter of the sample was fixed at 5 mm by comparing the requirements on resolution (susceptibility $\kappa = 10^{-4}$ in the solenoid's induction $B_S = 0.1$ T) with the integrator drift, and by considering the manufacturing limits on accuracy in the cross-section of the sample. The length of the sample was chosen to be 45 mm resulting from field calculations made with the computer program POISSON: the coefficients D and D_ℓ are of the order of 1 % and the length is small enough to keep the sample in the homogeneous field (to within 2 %) of the solenoid - a condition which is assumed in the calculation of D. The computed D and D_ℓ are given in Table 1.

The length of the search coil was chosen to be 15 mm, assuring an induction uniformity of better than 0.1 % over its length. The adopted winding method made it possible to obtain an inner diameter of 5.6 mm for the air-cored coil.

TABLE 1

Computed factors D and D_ℓ

κ	D	D_ℓ
0.01	0.0065	0.0079
0.1	0.0069	0.0085
0.5	0.0094	0.0119
1.0	0.0115	0.0147

2.4 - Design of the permeameter

To permit measurement at various temperatures, the permeameter is mounted inside an inverse cryostat immersed in the liquid helium of the solenoid's cryostat (Fig. 1). Up to eight samples can be mounted on canevasit rods and measured successively without opening the cryostat. Sample selection and sample movement inside the search coil are controlled at room temperature. The latter is automated using a stepping motor to minimize the integration time. Special care has been taken in the design to minimize the thermal losses, match the contraction coefficients and use nonmagnetic materials in the critical parts.

The measuring coil is made of 12'000 turns of 0.045 mm diameter enamelled copper. They are wound on a Teflon core which is demounted after coil impregnation with epoxy resin.

To obtain a direct display of susceptibility, the time constant of the integrator is adjusted to $\tau = 0.2322$ s and the voltage from the integrator is divided by the solenoid induction B_S in a high precision voltage divider.

An automatic sequence opens the integrator, controls the sample movement and triggers the display.

2.5 - System performance

Factors affecting the accuracy of susceptibility (equation 3) can be determined with a precision of better than 10^{-3}. The practically achievable tolerance of 0.01 mm on the sample diameter limits the accuracy of the measurement to 0.4 %.

The reproducibility is limited by the erratic integrator drift. The dispersion of ten measurements at $B_S = 1$ T on stainless steel AISI 316LN is less than $\Delta K \approx \pm 0.00001$. This value corresponds well with the drift calculated on the basis of 0.2 µV for the amplifier's low frequency input noise and a typical 3 s duration of a single measurement.

2.6 - Results

Values of permeability measured on some low-µ materials are given in Table 2.

TABLE 2

B_S [T]	AISI 316LN			AISI 316LN (TIG-weld)			INCONEL 718 (heat treated)		
	4.2 K	78 K	293 K	4.2 K	78 K	293 K	4.2 K	78 K	293 K
1	1.0252	1.0077	1.0027	1.0280	1.0082	1.0029	1.1578	1.0594	1.0031
2	1.0214	1.0075	1.0027	1.0230	1.0080	1.0029	1.0897	1.0444	1.0031
3	1.0183	1.0074	1.0027	1.0194	1.0079	1.0029	1.0642	1.0356	1.0031
4	1.0161	1.0072	1.0027	1.0170	1.0077	1.0029	1.0506	1.0301	1.0030
5	1.0145	1.0071	1.0027	1.0153	1.0075	1.0029	1.0422	1.0261	1.0030
6	1.0133	1.0070	1.0027	1.0140	1.0074	1.0029	1.0361	1.0236	1.0030

Although this permeameter was designed specifically for the range $1 < \mu_r < 2$, it has also been successfully used for measurements on low carbon steel (C ≈ 0.25%, P = 0.1 %, S = 0.063 %) in the saturation region (see Table 3). To minimize the D factor and to reduce the force exerted on the sample, its diameter was decreased to 2 mm.

The accuracy on ($\mu_r - 1$) in Table 3 is 0.5 % (2 % for $B < 2.205$ T owing to the uncertainty in B determination). It follows from the results in Table 3 that for $B > 3$ T, the permeability is given by the relationship

$$\mu_r = \frac{B}{B - B_i^{SAT}} \,,$$

where $B_i^{SAT} = 2.157 \pm 0.01$ T is the saturation intrinsic induction. This value agrees, to within the accuracy of the measurement, with that found in the ring test method.

TABLE 3

Permeability of low carbon steel in the saturation region at 4.2 K

B_S [T]	B [T]	μ_r	B_i [T]
0.1	2.205	24.231	2.114
1	3.147	3.163	2.152
2	4.152	2.081	2.157
3	5.154	1.7197	2.157
4	6.154	1.5396	2.157
5	7.154	1.4316	2.157
6	8.154	1.3597	2.157

3. - Ring permeameter measurements

3.1 - Measuring equipment

Permeability measurements may be performed at ambient, liquid nitrogen and liquid helium temperatures on ring samples having the following dimensions: outer diameter 114 mm, inner diameter 76 mm, thickness 12 mm.

For measurements at ambient temperature, a split-coil permeameter(1) is used. A maximum magnetizing force of 24'000 A/m is reached with an excitation current of 40 A.

While the above construction facilitates the exchange of samples, the total resistance of the excitation coil is inherently high due to the large number of contacts (two per turn) and the maximum magnetizing force is restricted by the power dissipation at high currents. Thus, for low temperature measurements, the flux-measuring and excitation coils are wound directly onto the sample using a toroidal winding machine. A maximum magnetizing force of 818'000 A/m has been reached in liquid helium with 90 A in an excitation coil of 2727 turns, wound with 1 mm diameter copper wire.

The layout of the measuring system is shown in Fig. 2. The measuring sequence, which has already been described in Ref. 1, is remotely-controlled by mini-computer(2). Interactive programs permit the definition of sample dimensions, desired excitation currents and requirements for demagnetization and pre-measurement cycling of the sample. The measured data are treated online and results are produced on a line printer and/or CRT.

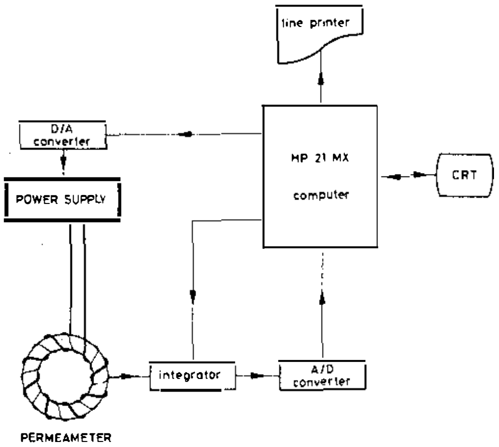

Fig. 2

Layout of the ring permeameter

3.2 - Measurement accuracy

The integrator time constant is measured with an accuracy of 0.3 ^{o}/oo and the sample cross-section is known with an accuracy of 0.7 $^{o}/oo$. The resolution of the ADC corresponds to 0.0005 T. After correction for the flux which is external to the sample but links the measuring coil, the overall accuracy of the measurement of the average induction $\overline{B}$ is thus 1 $^{o}/oo$ ± 0.0005 T.

Two power supplies are used to cover the working range of current. At present, the supplies have different accuracies so that the magnetizing force is known with an accuracy of 0.4 $^{o}/oo$ at field levels above 6'128 A/m and with an accuracy of 2 $^{o}/oo$ at lower field levels. The measured average induction $\overline{B}$ is corrected according to its radial distribution in the sample as described in Ref. 1.

3.3 - Results

Measured data for one low-carbon steel, whose composition is given in Section 2.6, are presented graphically in Fig. 3 for ambient and liquid helium temperatures.

At liquid helium temperature, the intrinsic induction in the range $\overline{B} = 2.7 - 3.2$ T was found to be constant and equal to $B_i^{SAT} = 2.162 \pm 0.006$ T which compares favourably with the value found in Section 2.6.

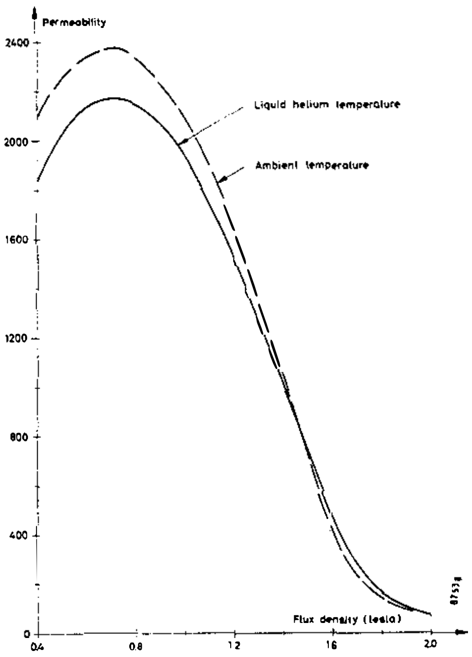

Fig. 3

4. - Conclusion

The two permeameters are complementary in their permeability range.

These devices have been employed to select the materials used in the construction of the prototype superconducting magnet for the CERN Intersecting Storage Rings (subjet of another paper submitted to this Conference).

References

1) K.N. Henrichsen, Permeameter, Proc. 2nd International Conference on Magnet Technology, p. 735, Oxford (1967).

2) K.N. Henrichsen and L. Walckiers, A computerized quench-recording and control system for superconducting magnets, Paper presented at this Conference.