EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN LEP-MA/83-44

LARGE SCALE MAGNETIC FIELD MEASUREMENTS AND MAPPING

by

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Invited Paper Presented at 8th International Conference on Magnet Technology,
Grenoble, France, 5 - 9 September 1983

Geneva, Switzerland
September 1983

Résumé - Cet article fait le point sur les techniques les plus récentes en matière de mesures magnétiques à grande échelle, en indiquant les principaux problèmes liés à la cartographie du champ magnétique. Le développement de la microélectronique au cours des dernières années a créé une révolution dans les systèmes de mesures magnétiques. L'émergence de matériels et logiciels modulaires, ainsi que l'usage répandu de standards industriels ont influencé l'architecture des systèmes de mesure. L'intégration de microprocesseurs dans l'équipement et la mise en oeuvre d'algorithmes modernes ont amélioré les performances des sondes de mesure et simplifié leur calibration. Tout système moderne présente également la possibilité d'analyse et de visualisation en ligne des résultats de mesure, ainsi que la détection et le diagnostic précoces des pannes.

Abstract - The paper illustrates the most recent techniques in the field of large-scale magnetic measurements. The main problems related to field mapping are discussed. The development of microelectronics during the last few years has created a revolution in magnetic measurement systems. Modular hardware and software as well as widely used industrial standards have influenced the architecture of measurement systems. The use of embedded microprocessors in the equipment and the application of modern algorithms have improved the performance of measurement probes and simplified their calibration. A modern system also provides facilities for on-line analysis and display of measurement results as well as early detection and indication of equipment faults.

I - INTRODUCTION

The problem in large-scale magnetic measurements is to obtain the necessary accuracy for the field map within the period allocated to the measurements. The time is usually limited when the measurements are scheduled sometime near the end of a construction period and even more, if the magnet has already been installed as part of an existing accelerator and the measurements must be performed during periods of access to the machine. In addition, it is important that the measurements are fully completed and certified correct before the installation of detectors, vacuum chambers and other components within the magnetic field volume.

These requirements call for a detailed analysis of the task, a careful design of the measurement equipment and a clear idea of the way to present and judge the measurement results. Some model work is often useful and may save considerable time.

It is curious to note that while the measurement methods have remained virtually unchanged for a very long period, the equipment has been subject to continued development. In the following, only the two most commonly used methods will be mentioned. For a more complete description of the many other existing measuring methods, reference is made to two classical bibliographical reviews [1,2].

II - THE FLUXMETER METHOD

Based on the induction law, this method is the most ancient [3] of the currently used methods for magnetic measurements, but it can be very precise [4]. It is also the most precise method for the measurement of the direction of magnetic flux lines. Measurements are performed either using fixed coils in a dynamic magnetic field or by moving the coils in a static field. The coil geometry is often chosen to suit a particular measurement. One example is the Flux ball [5] which was of rather complex construction and which was used for point measurements in inhomogeneous fields. The coil method is particularly suited for measurements with long coils in beam guiding magnets [6], where the precise measurement of the field integral along the particle trajectory is the main problem. In this case, the geometries of the measurement coils are chosen so as to link with selected field components [7].

Induction coils were originally used with a ballistic galvanometer and later on with more elaborate fluxmeters [8, 9]. The coil method was improved considerably with the introduction of the classical electronic integrator, the Miller integrator, but it remained necessary to employ difference methods in precision measurements [10]. The advent of digital voltmeters made fast absolute measurements possible and the Miller integrator has remained the most popular fluxmeter. With the development of solid state d.c. amplifiers, this integrator has become inexpensive and is often used in multi-coil systems [11, 12, 13]. The main problems with the Miller integrator are now related to the integrating capacitor [14].

A few electronic integrators have been developed by industry and are commercially available. They are, however, relatively expensive and the choice is rather limited. In recent years, a new type of electronic integrator has been developed, which is based on a high quality d.c. amplifier connected to a voltage-to-frequency converter and a counter. This system is well adapted to digital control but imposes limits on the maximum size of the input signal, or in other words the rate of change of the flux.

The sensitivity of the fluxmeter method depends on the effective coil surface and the quality of the integrator. The coil-integrator assembly can be calibrated to an accuracy of 10 ppm in a homogeneous magnetic field with reference to a nuclear magnetic resonance probe.

III - THE HALL PROBE METHOD

Nowadays, the most commonly used method in field mapping [15, 16, 17, 18] is the Hall probe method. It is the simpler and faster of the two methods considered here, but also the less precise.

E.F. Hall made his discovery in 1879 [19] and in 1910, magnetic measurements were performed using this method [20]. It was, however, only around 1953 that suitable semiconductor materials were developed [21, 22] and since then the method has been used extensively.

Several factors set limits on the obtainable accuracy, the most serious being the temperature coefficient of the Hall voltage. Temperature stabilization is usually employed in order to overcome this problem [18, 23, 24]. It may also be taken into account in the probe calibration by monitoring the temperature during measurements [25]. The temperature coefficient depends, however, on the level of the magnetic field [25], so relatively complex calibration tables are needed. Another complication can be that of the planar Hall effect [26], which makes the measurement of a weak field component normal to the plane of the Hall plate problematic if a strong field component is present parallel to this plane. Many possible remedies have been proposed [27] but they are all relatively difficult to apply. Last but not least is the problem of the representation of the calibration curve since the Hall coefficient varies with the magnetic field. The Hall probe of the cruciform type [28] shows a better linearity and has a smaller active surface than the usual rectangular plate. Its magnetic centre is, therefore, better defined, so it is particularly well suited

Table 1 - Hall probe characteristics

Type: Siemens	Geometry	Nominal Current [mA]	Hall voltage at 1 T and nominal current [mV]	Temperature coefficient β [ppm/°C]	Active surface [mm ²]
FC32	rectangular	100	150	-400	8
SBV 579	cruciform	100	130	-400	2.6
SBV 601	cruciform	100	150	-500	1.0
SBV 601-S1	cruciform	200	30	- 30	1.0
SBV 585	cruciform	50	100	-900	0.02
SBV 585-S1	cruciform	100	50	- 70	0.02

for measurements in strongly inhomogeneous fields. Special types, which have smaller temperature dependence, are available on the market, but these probes show a lower sensitivity. Table 1 gives some typical characteristics of various Hall probes [29].

The measurement of the Hall voltage sets a limit of about 1 G on the sensitivity and resolution of the measurement if conventional direct current excitation is applied to the probe. The sensitivity can be improved considerably if alternative current excitation is used [30, 31]. A good accuracy at low fields can then be achieved by employing synchronous detection techniques for the measurement of the Hall voltage.

Hall plates are usually calibrated in a magnet in which the field is measured simultaneously using a nuclear magnetic resonance probe. The calibration curve is most commonly represented in the form of a polynomial of relatively high order (9 or more) fitted to a sufficiently large number of calibration points. This representation has the advantage of a simple computation of the magnetic induction from a relatively small table of coefficients.

A physically better representation is the use of a piecewise cubic interpolation through a sufficient number of calibration points which were measured with high precision. This can be done in the form of a simple Lagrange interpolation or even better with a cubic spline function. The advantage of the spline function comes from its minimum curvature and its "best approximating" properties [32]. The function adjusts itself easily to non-analytic functions and is very well suited to the interpolation from tables of experimental data. The cubic spline function is a piecewise polynomial of third degree passing through the calibration points and defined such that the derivative of the function is continuous at these points. Very efficient algorithms can be found in the literature [33]. The calculation of the polynomial coefficients may be somewhat time-consuming but need only be done once at calibration time. The coefficients (typically about 60 for the bipolar calibration of a cruciform Hall plate) can be easily stored in a modern device [24] and the subsequent field calculations are very fast. The quality of the calibration function can be verified from field values measured between the calibration points. A well designed Hall-probe assembly can be calibrated to an accuracy of 100 ppm.

IV - MEASUREMENT BENCHES

The mechanical gear for moving and positioning the measurement probes inside the magnetic volume is usually designed for each specific application, the shape and symmetries of the magnetic field determining the probe movements and the choice of coordinate system. A few "universal" field mappers have been built [23, 34, 35]. In general, standardization is difficult to achieve but may occur in the design of modular probe assemblies and rail-arrangements for carriage movements [36]. This situation may change when industrial robots will become part of our measurement systems.

An example of a recent large-scale field mapping was the measurement [37, 38] of the CERN-UA1 dipole magnet with its useful inner field volume of about 70 m³. Figure 1 shows the measuring gear mounted inside the dipole. A large aluminium frame carried a

total of 70 Hall probes, 66 of which measured the main component of the field at 10 cm intervals around the periphery of the frame, while the remaining four measured the two perpendicular components for checking purposes. The frame traversed the field volume at 10 cm intervals and finally moved vertically at either end of the volume so that the outside surface of half of the complete field volume was measured. Assuming symmetry with the other half of the volume the total field in the magnet was evaluated from these boundary conditions [39]. This type of field evaluation can be done with reasonable accuracy if the field shape is not too complex.

A special probe array was necessary for more precise measurements along the beam path over a total length of 12 m. 75 Hall plates measured the field in all three dimensions on a mesh of 50 mm.

Another example was the measurement [40] of the large angle magnetic spectrometer (LAMS) which forms part of the CERN-UA2 experiment. This magnet has a smaller volume but a more complex field pattern, which favoured the choice of a spherical coordinate system. The measurement arrangement is shown in Fig. 2. A

3 m long rail was fixed at one end, pivoting about the magnet vertex. It carried a Hall-plate assembly for measurements in three dimensions, travelling along the rail. In addition to the Hall-plate measurements, a 2.75 m long integrating induction coil was employed in order to monitor the measurement quality. Due to the very inhomogeneous field, it was necessary to take into account the variation in width along the length of this coil. The same equipment, but with a different support structure, was used for the field measurements of the toroidal magnets mounted at each end of the spectrometer.

Fig. 1 - UA1 field mapper

Fig. 2 - UA2 field mapper

V - SYSTEM ARCHITECTURE

The structure of measurement systems has grown in complexity as the measurement tasks increased in size. The need for automation called for the use of digital electronic techniques. As in many other fields, the advent of the mini-computer was the first step in the direction of full automation. The hard-wired logic circuits designed and built for a specific task were replaced by programmable systems which were commercially available. By connecting his measurement equipment to the computer, the user could profit from the flexibility of a programmable system and from the advantages of mass data storage in a portable form, suitable for later processing on a large computer. On-line data handling combined with simultaneous graphic display of measurement results provided a powerful tool for early detection of faults in the measurement equipment or in the operation of it. An important step forward in standardization was the use of CAMAC equipment linking the measurement machines to the computer [11, 13, 16, 18, 35].

The microprocessor revolution has now in turn influenced the design of magnetic measurement equipment. Embedded microprocessors discharge the control computer to a large extent. Tasks which consume processing time and memory space can be delegated to microprocessors distributed within the system. This allows a modular structure of the equipment which makes the design and programming of the measurement system easy and provides an efficient use of resources. The necessary data-bases are located within the equipment modules but are accessible from the controller for checking and identifying purposes. Data reduction can also be done locally and may limit considerably the amount of data transmission within the system. Diagnostic programs may be resident in the modules and will allow the specialist to perform the running-in and debugging of his equipment through the controller. This form of access makes maintenance and repair easier too. The use of digital rather than analog multiplexing techniques solves many problems related to earth connections, contact potentials and common mode signals.

The application of widely used industrial standards, such as the General Purpose Interface Bus (GPIB), IEEE standard No. 488-1978, or the computer communication standard RS-232-C for the interconnection of the various equipment modules, will largely facilitate the use of commercially available instruments and will allow an extreme flexibility even in a complex system. An example of a microprocessor-based equipment assembly is shown in Fig. 3.

A dual-level structure was chosen. The work station at operator level communicates with the various microprocessors at equipment level through the GPIB which forms the backbone of the system. Messages consisting of strings of printable characters are transmitted bi-directionally through the GPIB. Direct communication

between modules at equipment level as well as simultaneous transmission to two or more modules is also possible. The only disadvantage of the GPIB standard is its distance restriction of about 20 m.

Fig. 3 - Microprocessor-based measurement equipment

The GPIB-controller can, depending on the needs for flexibility or speed, be programmed either using an interpretive language like BASIC or a compiled language like PASCAL. A large variety of GPIB-controllers, ranging from the simple desk calculator to the powerful multi-tasking minicomputer, are at present available on the market. A number of systems such as the one described are presently used for the various tests and measurements of the LEP magnets [41].

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