CERN LIBRARIES, GENEVA

CM-P00064349

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN ISR-BOM/81-16

THE POLAR CO-ORDINATE MAGNETIC MEASURING SYSTEM FOR THE AXIAL FIELD
SPECTROMETER MAGNET AT THE ISR-CERN

by

D. Swoboda

Presented at the 7th International Conference on Magnet Technology,
Karlsruhe, Federal Republic of Germany
March 30 - April 3, 1981

Geneva, Switzerland

March 1981

D. Swoboda

Abstract - A system for the measurement of three-dimensional magnetic fields with nearly axial symmetry is described. The apparatus, which was used for the mapping of the field volume in the axial field spectrometer magnet of the ISR, measures in polar co-ordinates. The choice of the co-ordinate system and its advantages over other possible configurations is explained with particular reference to the measured magnet. The design and operation of the measuring system is described in detail, and its performance is discussed.

1. INTRODUCTION

The AFM spectrometer magnet is presently installed in intersection 8 of the CERN Intersecting Storage Rings. The particular features of this large dipole magnet are the conical poles bearing circular coils and the asymmetrical return yoke (Fig.1).

Fig. 1. Axial Field Magnet during measurements.

For particle analysis an accurate field map had to be established extending to an outer radius of 250 cm from the centre of the magnet. Precision requirements, as well as considerations of the shape and symmetry of the magnetic field (Fig.2), favoured a division of the field map into three separate zones.

Fig. 2. Plot of AFM field.

Due to the azimuthal field symmetry in the volume between pole faces, magnetic measurements in one plane only of the longitudinal and the radial field components were adequate in the central region. Beyond a distance of 250 cm from the centre of the magnet, the measurement of the three field components in a very large mesh grid was sufficient. The critical region lies between these two zones. The tolerated error of 5% of nominal field and the increasing azimuthal asymmetry of the magnetic field at larger radii made the measurement of the three field components indispensable for radii beyond the pole faces.

In this paper, the measuring bench constructed for the mapping of this zone is described and the choice of polar co-ordinates is explained.

2. CHOICE OF THE CO-ORDINATE SYSTEM

The constraints imposed by the geometry of the magnet and the shape of the magnetic field governed the selection of a suitable co-ordinate system. However, the mechanical conception of the measuring machine was equally important. The requirements for precision and the close time schedule allocated for the field mapping had to be taken into consideration, making it necessary to avoid complexity of the apparatus and complicated manual interventions.

A polar co-ordinate system obviously fits best the shape of the magnetic field. With the origin at the centre of the magnet, it involves only one linear displacement, the other two being rotations about the origin. In this way, the shape of the pole pieces does not create any restrictions to the possible volume to be measured. Furthermore, the azimuthal field symmetry can easily be checked. The requirements for the resolution of the field maps are best met since the density of the measured points is inversely proportional to the radius.

2.1 Determination of the Measuring Grid

The outer boundary of the accessible volume is given by the distance from the centre of the magnet to the base beam in the radial direction.

The polar angle is limited by the conical pole pieces. The required inner radius is determined by the expected field symmetry in the volume between the pole faces. Using the computed field map, the step size was chosen to be such that the variations of flux density between neighbouring points should not exceed 200 G.

The resulting parameters are listed below:

Name	dimension	comment
Radius	$70 \leq r \leq 250$ cm	overlaps 10 cm of central region
Polar angle	$42^\circ \leq \theta \leq 90^\circ$	clearance of 2° towards pole
Azimuthal angle	$-90^\circ \leq \phi \leq 270^\circ$	
Radial step size	$\Delta r = 5$ cm	
Angular step size	$\Delta \theta = 5^\circ$ $\Delta \phi = \text{free}$	

Manuscript received March 30, 1981.

The author is with CERN, ISR Division, 1211 Geneva 23, Switzerland.

3. METHOD OF MAGNETIC MEASUREMENT

A convenient and commonly used method to map magnetic fields is by means of Hall plates. The small size of the sensitive area of the semi-conductor makes it possible to measure the flux density in a nearly point-like volume. The direct dependence on the magnetic field of the voltage generated across the plate facilitates the signal processing. Furthermore, the response time is very short.

For precise measurements, however, several precautions must be taken. In addition to the temperature dependence of the Hall voltage, the measured value is affected by the orientation of the plate with respect to the direction of the field and by gradients.

3.1 Influence of Probe Orientation

The generated Hall voltage, for a fully temperature stabilized probe, can be expressed by the following equation [1]:

$$V_H = C_1 i B \sin\phi \quad (=V_N) \\ + C_2 i B^2 \cos^2\phi \cos\theta \sin\theta \quad (=V_P) \quad (1) \\ + R i [1 + C_3 B^2(1 - \cos^2\phi \sin^2\theta)] \quad (=V_i)$$

C_i = constants
 ϕ = angle of B with respect to plane of Hall plate
 θ = angle between the projection of B onto the plate and the direction of i
 B = magnetic field
 i = Hall current
 R = resistance of Hall plate

The planar Hall effect has been measured for the type of Hall plate (Siemens SBV 579) [2] used for the field mapping of the AFM. At the calculated nominal field ($B_{nom} = 0.6$ T), the maximum error to be expected was found to be $V_p \sim 10^{-3}$ V. This corresponds to a field error of approximately $\Delta B = 70$ G.

However, the angular dependence of the Hall voltage provides a possibility to compensate for all terms which are not proportional to the flux density. A rotation of the Hall plate about an angle $\Delta\phi = \pi$ yields:

$$\sin\phi' = \sin(\phi + \Delta\phi) = -\sin\phi \quad (2)$$

$$\text{hence } V_H - V_H' = 2 C_1 i B \sin\phi \quad (3)$$

which is strictly proportional to the field normal to the Hall plate. In this case the measurement of a small field component in the presence of a large component parallel to the probe is only influenced by the mechanical tolerances of the rotation.

3.2 Influence of Probe Alignment

The tolerable alignment error is obtained by considering the required resolution of the measurements in conjunction with the prevailing field gradient. The maximum admissible error in measured field due to misalignment was ± 29 G. Near to the coils, where the gradient is strongest, this leads to polar and radial position tolerances of ± 1.4 mrad and ± 1 mm, respectively.

4. DESCRIPTION OF THE MEASURING EQUIPMENT

Functionally, the system can be divided into three separate units (Fig. 3), namely the mechanical gear which enables the movement of the probe holder along the co-ordinates, the probe holder assembly which contains the measuring heads, and the Teslameters.

Fig. 3. Schematic layout of the measuring system.

4.1 The Main Mechanical Apparatus

To avoid complexity, only the most frequent movements were made automatic. The radial displacement of the probe holder as well as the rotation about the polar angle necessitate manual intervention. This reduces the weight of the apparatus enabling reproducibility of the movements without a noticeable loss in measuring speed.

For the azimuthal motion of the gear, an aluminium tube of 20 cm in diameter, suspended at both ends in the circular holes of the pole faces, rotates about its length axis. It is driven by a stepping motor via a reduction box. A reduction ratio of 1:450 is suitable for the conversion time $t_c = 200$ ms of the Teslameters and the available stepping motor. The resulting frequency of the motor (200 steps/turn) corresponds to a time of 10 min for a full revolution of the tube axis.

The polar angle is covered by pivoting a light-weight arm, extending to a radius of 200 cm, about a transverse axis passing through the centre of the aluminium tube. The arm consists of a welded aluminium framework [3] calculated to provide adequate rigidity with minimum inertia. A disc-sector which is dowelled to the arm, bears conical holes drilled accurately every 5° at its perimeter. The desired polar angle is obtained by a locating bolt which joins the appropriate hole in the disc with the matching threaded hole in the aluminium tube.

For radial displacement, the probe holder slides in a precisely machined aluminium dove-tail which is bolted to the arm. The desired probe position is obtained by inserting a bolt with a conical end into one of the threaded holes located every 5 cm in the base of the dove-tail, holding the probe holder in place.

Since it was expected to measure the magnetic field with the photomultiplier stacks installed on the base beam, the probe holder protrudes by 55 cm for the radius of 250 cm covered by the measuring bench.

Alignment of the apparatus - The suspension of the aluminium tube inside the holes in the pole faces of the magnet (Fig. 4) can be adjusted in the vertical, lateral and longitudinal directions by use of screws. The centering of the tube within the holes was controlled with dial gauges.

The disc-sector giving the polar angle was aligned and dowelled to the arm during assembly of the gear. The intersection of the axis of the dove-tail with the magnet axis can be adjusted with a differential screw which causes a rotation of the dove-tail with respect to the arm. The absolute azimuthal position of the probe holder is software controlled.

Fig. 4. Assembly of main suspension installed in dummy pole.

4.2 The Probe Holder

The ten probe heads are alternately orientated so as to measure the radial field component in the "odd" and the angular components in the "even" positions (Fig. 5). The probe holder is consequently designed as an active unit, which enables the rotation of the "even" probes to measure both angular components.

Fig. 5. Probe holder assembly showing arrangement of Hall plates

The probe heads are installed in an aluminium profile casing at a precise spacing of 5 cm, corresponding to the radial step width, between probe centres.

Rotation of the probe support about its length axis is provided by a lightweight purpose-built air motor (Fig. 6). The angular positions are determined by the rotation of the cam. A pneumatic piston pushes a wedge shaped notch into the cam to obtain the central position. In this location, the "even" Hall probes are orientated to measure the polar field component. The azimuthal field is measured twice by turning the probe-holder to $\psi = -90^\circ$ and subsequently to $\psi = +90^\circ$. By taking the difference of these measurements the influence of the parallel component is eliminated.

Fig. 6. Cross-section of probe holder drive.

The measurement of the three field components in ten radial positions requires the displacement of the probe holder assembly by the distance of one locating hole inside the dove-tail.

Alignment of the probe holder - Screws, acting directly on the air motor, provide the angular adjustment of the probe holder. For the longitudinal alignment, a differential screw shifts the probe holder assembly with respect to its shoe.

4.3 The Teslameters

Each of the ten Hall probes is individually controlled by its assigned Teslameter [4]. All probe functions, such as temperature, Hall current and voltage are microprocessor controlled in the Teslameters, where the Hall voltage is also converted into tesla. The buffered output allows the simultaneous triggering of all Teslameters while they can be read individually before the next measurement is triggered. This feature permits the continuous rotation of the bench during measurement.

Hall probes - The Hall plates are of the type SBV 579. Each Hall plate is housed in a small copper block which also contains the heating resistors and platinum probe for temperature control to keep the temperature at a constant value of about 35°C .

The thermally insulated copper block is aligned inside an aluminium box by means of a set of adjustment screws (Fig. 7).

Alignment of Hall plates - The copper block and the aluminium box were machined to tolerances of less than 0.05 mm. The adjustment screws were prepositioned with a micrometer before inserting the copper block in the aluminium casing. The magnetic centre of the complete probe was then checked in the gap of a permanent magnet, fitted with pointed pole tips, to a precision of better than 0.05 mm.

Fig. 7. Opened measuring head.

Calibration of the Hall probes - The Hall probes were calibrated against NMR in the gap of a calibration magnet over a field range of ± 1.3 T. Ten calibration points were measured for each Hall plate. The coefficients of a third-order spline fit through these points were burnt into the EPROM of the corresponding Teslometer. The stability of the probe characteristics were checked throughout the period of the measurements.

6. SOFTWARE

An HP2100 computer was employed for the control of the measuring machine. The acquired data was written on magnetic tape, and the final field map was processed on the CDC 7600.

A standard data base containing all relevant parameters simplified the operation of the measuring bench and prevented repetition or omission of measurements. However, the interactive control mode gave the choice between different operation programs and parameters. Deviations from the standard data base were signalled by the computer, but operation resumed after confirmation.

Different procedures were implemented for recovery after hardware faults during a measurement run. A special option enabled the on-line check of the azimuthal field symmetry. A measurement set included the field values measured during three azimuthal excursions of alternating sense through an angle $\phi = \pi$ of the arm with the probe holder in one radial position. At the end of each half revolution, the probe holder turned by $\psi = 90^\circ$ about its length axis before the movement of the arm was reversed. The required Teslometers were triggered every 5° during the rotation of the bench. All acquired data was stored in core until completion of the entire set. If no faults were recorded during the measurements, the field values together with the corresponding parameters for co-ordinates and identification were written on magnetic tape.

7. SYSTEM PERFORMANCE

7.1 Mechanical Accuracy

The maximum deflection of the measuring arm was computed to be $z=0.755$ mm [3]. This corresponds to an average error of polar angle $\Delta\theta$ of 0.377 mrad. Measurements on the loaded arm confirmed this value.

The uncertainty of the absolute encoder is given by $\Delta\phi_1 = \pi/8192 = \pm 0.383$ mrad. The maximum deflection of the arm in this direction yields an average angle of $\Delta\phi_2 = \pm 0.88$ mrad, increasing the total error in azimuthal angle to $\Delta\phi = \pm 1.263$ mrad. The radial precision could be estimated with the following tolerances:

- circular holes in the pole faces	± 0.5 mm
- alignment of the longitudinal axis of measuring machine inside these holes	± 0.05 mm
- precision of the probe holder	± 0.05 mm
- positioning of the probe holder	± 0.1 mm
- total radial positioning error	± 0.7 mm

It can thus be seen that the mechanical accuracy of the measuring apparatus stayed well within the defined limits.

7.2 Reproducibility of the Measurements

The program for on-line test of the field symmetry was used to check the reproducibility of the measurements. In this case, after moving the probe holder into various positions, the measurement in the initial location was repeated.

The difference between both readings was found to be always less than $\Delta B = \pm 1$ G. This is of the same order of magnitude as the resolution of the Teslometers.

ACKNOWLEDGEMENTS

The author is particularly indebted to T.M. Taylor for many useful discussions and encouragement. Thanks are due to G. Trinquart for active participation in the design and to C. Sanz, G. Turcato and P. Vallois for useful work in the construction. The assistance of K. Brand and G. Brun was equally deeply appreciated.

REFERENCES

- [1] R. Braunersreuther, M. Van Gulik, S. Gustar, D. Lehm, "Magnetic field measurements for the Synchro-cyclotron improvement programme", CERN PS-COP/77-39, 1977.
- [2] O. Runolfsson, "Magnetic measurements in high-energy physics experiments", Proc. 6th Int. Conf. on Magnet Technology, Bratislava, Czechoslovakia, 1977, pp. 802-812.
- [3] C. Hauviller, Private communication.
- [4] K. Brand and G. Brun, "A digital Teslometer", CERN 79-02, 1979.