PRECISE SEMI-AUTOMATIC FIELD MAPPING IN THE SPLIT FIELD MAGNET OF THE ISR

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Abstract

The computer-controlled equipment for the magnetic measurements of the Split Field Magnet System of the CERN Intersecting Storage Rings is described. Three different measurement machines are necessary for the measurements of this large and complex magnet system. The strongly inhomogeneous field is measured to a precision of 1 °/oo of maximum field using Hall-plate assemblies. The final data treatment includes the smoothing out of the established scalar potential by solving the Laplace's equation from the conditions at the boundaries by means of relaxation. The three-dimensional field map will be used for particle analysis. Effects of the SFM-field on the circulating ISR beams are evaluated and optimized.

I. Introduction

The Split Field Magnet[1] is a large analysis magnet system which will be placed in one of the intersection points of the CERN Intersecting Storage Rings (ISR). The layout of the magnet system is shown in Fig. 1. It contains the Split Field Magnet (SFM), the small compensator magnets (SCM), the large compensator magnets (LCM), and the magnetic beam channels (MC).

The magnetic field in the SFM must be known everywhere inside the useful volume to an accuracy of 1 °/oo of the maximum value. Since the field is strongly non-uniform, it has to be measured point by point on a relatively dense three-dimensional grid. These measurements must be done at different field levels corresponding to a wide range of possible ISR beam momenta. The measured field distribution will be made available to the experimental physicists in such a form that they may be used straight away in particle tracking and momentum analyzing programs.

Another series of measurements called "orbit optimization" measurements is necessary to enable tracking of the circulating ISR beams through the entire magnet system. By an iterative sequence of measurements and computations, the optimum set-up of compensators and magnetic beam channels will be found, reducing the disturbance of the ISR beams to a minimum. These measurements can be restricted to the horizontal median plane of the system (where the field is vertical) and, transversally, to a relatively narrow zone around the beam trajectory.

Apart from the use of different measuring devices, the large volume under consideration (which in addition contains physical obstacles such as pillars, etc.) makes it impossible to execute a measuring sequence which starts on one edge of the grid and proceeds systematically through the whole arrangement. So the field must in any case be measured in a number of separate smaller zones and the measured values have to be regrouped in a properly ordered array afterwards. This requires a special organization of measurement control and data acquisition by the control computer.

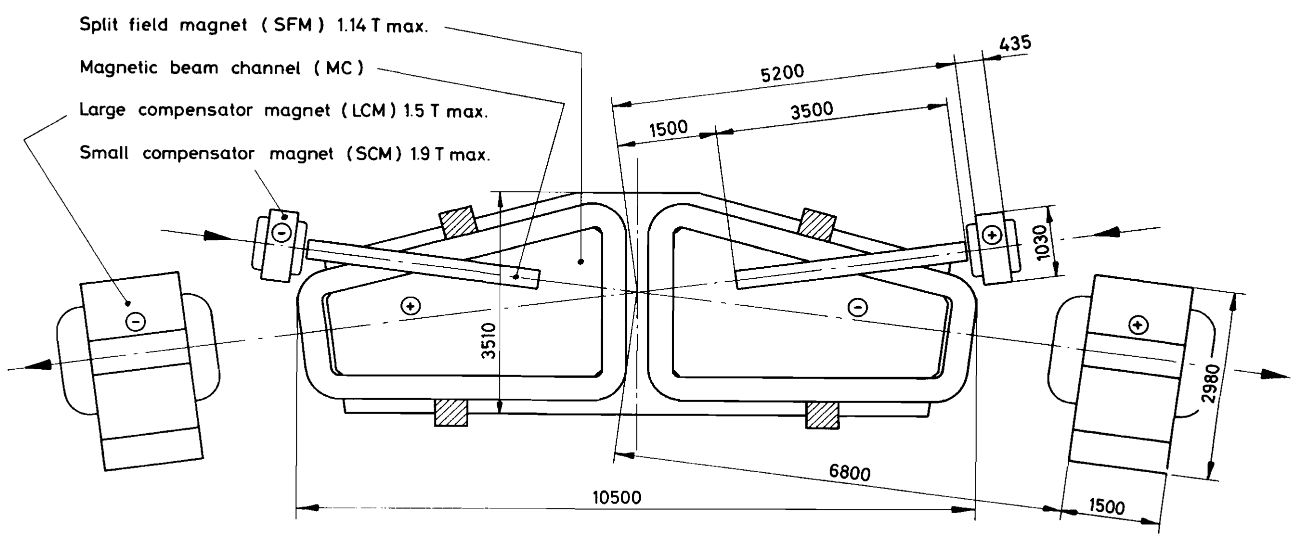

Fig. 1. General layout of the analyzing system (top view).

II. Measurement Method

The choice of the measuring system was determined by three main considerations:

- the large volume to be measured in a minimum of time;
- the inhomogeneity of the magnetic field;
- the measurement accuracy to be achieved everywhere in the volume.

Two systems were possible: rotating coils or Hall plates. The use of rotating coils would have involved a heavy and complicated mechanism. The measuring machine was made much simpler using Hall plates. The main difficulties arising are the effects due to the tangential field components on the measured Hall voltage.

1. The Hall Plates

The Hall plates used to measure the magnetic field are Siemens SBV 579 cross-formed type. Their main features are:

- Hall coefficient : 1.0 to 1.5 V/T.A
- temperature coefficient : - 0.7 $^{o}/oo$ / ^{o}C
- sensitive area : 1.6 x 1.6 mm^2 .

The advantages of a cross-formed Hall plate with respect to a rectangular plate are a smaller sensitive area, a better defined centre and a better linearity.

2. Calibration of the Hall Plates

The Hall plates were first calibrated with only a normal field component and then in the presence of a tangential field component producing a planar Hall effect, which had also to be measured in order to allow for its correction.

a) Normal calibration

This calibration was made in the uniform field of a reference magnet. The relation between Hall voltage and magnetic field was determined to an accuracy of $0.1 \cdot 10^{-4}$ T using an NMR probe. The calibration results were fitted to a seventh order polynomial. The resulting accuracy is about $0.5 \cdot 10^{-4}$ T.

b) Planar Hall effect measurement

In presence of a tangential field component, two sources of error can occur. An error in the orientation of the normal to the plate gives an error on the field:

$$\Delta B = B_T \cdot \sin \alpha \qquad \text{(II.1)}$$

where B_T = tangential field component,

and α = tilt of the plate.

The plates have a maximum tilt of 1 mrad, so that the influence of the tangential component on the measurement is 1 $^{o}/oo$ of the tangential field value. This determines the mechanical limit in the accuracy of the measurement.

An additional error, the planar Hall effect, is due to the difference between the transverse and the longitudinal coefficient of magnetoresistance. If ρ_o is the resistivity of the semiconductor material of the Hall plates without magnetic field (Fig. 2), the transverse and longitudinal magnetoresistance effects are:

$$\rho_1 = \rho_o (1 + \alpha_1 B^2) \qquad \text{(II.2)}$$

$$\rho_2 = \rho_o (1 + \alpha_2 B^2) \qquad \text{(II.3)}$$

The Hall voltage with tangential field is:

$$V_H = V_o + RB_z I - \left(\frac{\alpha_1 - \alpha_2}{2}\right) \rho_o B_T^2 I \sin 2\phi \qquad \text{(II.4)}$$

with V_o = residual voltage without field,
R = Hall coefficient,
I = Hall current.

The last term of this equation represents the planar Hall effect.

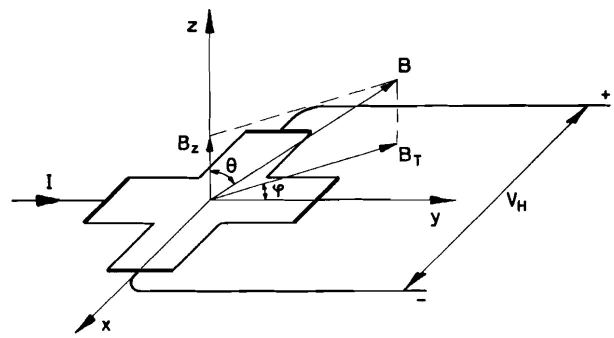

Fig. 2. Hall plate coordinate system.

In order to measure this term, a special device was built (Fig. 3) in which angles θ and φ can be set to any value. A coil surrounding the Hall plate is used to measure the normal field component to the plate. This component is known to within 10^{-4} T at a field of 1 T. The Hall plate is embedded in a copper block, which is temperature stabilized to within $0.1^{o}C$. The axis of the coil and the normal axis of the Hall plate can be set up collinear with the rotational axis about which φ is measured to within 0.1 mrad.

The Hall voltage measured with this device can be expressed by:

$$V_H = V_o + RB_z I + K_1 B_T^2 I \sin 2(\phi + \Delta\phi_1) + K_2 \,\varepsilon B_T \sin(\phi + \Delta\phi_2) \qquad \text{(II.5)}$$

ε being the angular misalignment of the Hall plate axis with respect to the ϕ rotation axis($\varepsilon \simeq 0.1$ mrad).

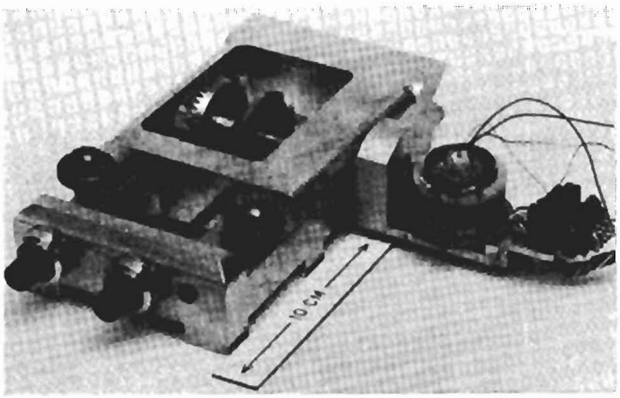

Fig. 3. The planar Hall effect study device.

A recording of V_H was made (Fig. 4) and it was found that equation (II.5) is verified to within $3\cdot10^{-4}$ T when B_T = 1 T and B_z = 0.

Only the characteristical points of this curve were measured: the four maximum and minimum values of V_H at approximately

$$\phi \simeq \frac{\pi}{4} + k\frac{\pi}{2}$$

and the four points where

$$\phi \simeq \Delta\phi_1 + k\frac{\pi}{2}$$

($\Delta\phi_1$ being the error on the origin of the angle ϕ, $\Delta\phi_1 \simeq$ 10 mrad).

ϕ and the last term of equation (II.2) were eliminated by computation and K_1 determined as a function of B_T. K_1 was found to depend only slightly on B_z and the field deduced by the normal calibration from the value of V_H independent of ϕ was slightly different from the normal field component found with the coil. This difference is less than $5\cdot10^{-4}$ T for all the selected Hall plates and for all the field values to be measured. If the influence of the planar Hall effect is corrected numerically, the geometrical error remains the main error in the magnetic field measurement by Hall plates in presence of a tangential field component.

3. Probes

Four probe assemblies were necessary to measure the different parts of the SFM system, each fitting one of the measurement machines described later. In order to limit the number of measuring points, each probe accommodates several Hall plates.

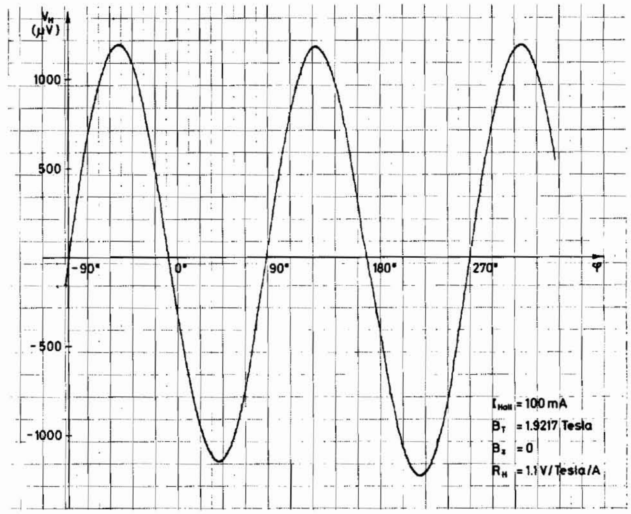

Fig. 4. Recording of the planar Hall effect.

a) Probe for the SFM machine (Fig. 5)

This probe is made from an aluminium tube in which 6 Hall plates are mounted at 100 mm intervals. Each Hall plate can be positioned and oriented with respect to its support by a three points suspension system. The support itself is held in place by two preadjusted pins which position the plate to within 0.01 mm and orient it to within 0.1 mrad. This probe is fixed at one end to the SFM machine. Any point up to a distance of 25 mm from an obstacle can be measured.

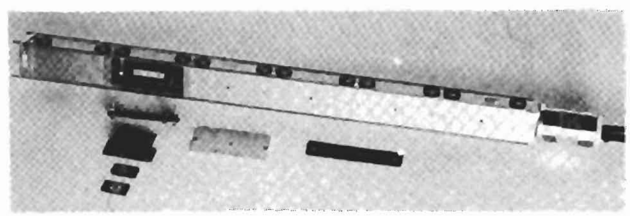

Fig. 5. The SFM probe

b) Probe of the LCM machine (Fig. 10 at the end of Section III)

This probe is made from an aluminium plate in which 3 Hall plates are mounted at intervals of 50 mm. The magnetic centre of each Hall plate was positioned to within 0.05 mm and was oriented to within 0.3 mrad. With this probe, measurements can be performed up to a distance of 10 mm from an obstacle.

c) Probes used for the "orbit optimization" measurements (Fig. 6)

Apart from the probe of the SFM machine, two other probes are used to measure the magnetic field along the beam trajectory for the orbit optimization measurements. One of these probes measures the field inside the magnetic beam channels and the SCM, with 7 Hall plates spaced by 25 mm. The second one measures inside the LCM and in the region between the LCM and the SFM, with 5 Hall plates spaced by 100 mm. In these regions (Fig. 13), there is no tangential field component so the design of these probes is much simpler than the design of the first two. The accuracy obtained is 0.1 mm in positioning and 5 mrad in orientation.

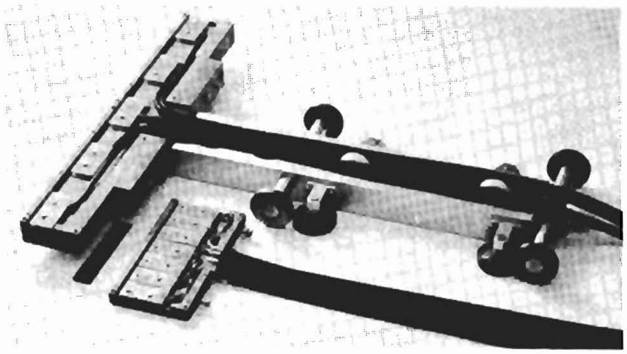

Fig. 6. The "orbit optimization" probe and the SCM/MC probe (not mounted).

III. Measurement Equipment

The measuring equipment is basically composed of three different machines, each designed to fulfil specific purposes:

1. The SFM measuring machine which has to explore the entire air gap of the magnet and part of the surrounding stray field region;
2. The LCM measuring machine;
3. The machine for measurements along the path of the incoming beams across the SCM and the MC.

The first series of measurements that have to be done are those for the orbit optimization. The SCM/MC machine is used as mentioned from the SCM up to the downstream side of the MC. The SFM machine then continues from this point towards the beams intersection and the edge of the pole. A fourth machine, identical in its principle to the SCM/MC type, will be used tracking the beam as it leaves the SFM pole towards the LCM and through it (Fig. 13). The second series of measurements is that of the complete analyzing volume offered by the system. The SFM machine is used for the whole of this volume apart for the LCM in which the field is measured separately with the LCM machine.

1. The SFM Measuring Machine

a) The structure of the machine (Fig. 7)

The three main parts of the machine are: the carriage (A), the transverse arm (B), and the slider (C). The transverse arm is rigidly fixed to the carriage forming an L-shaped structure. This structure can move longitudinally in the gap of the magnet by means of two rollers moving on a longitudinal guiding rail (D) which is mounted on the lower pole pieces, and one roller running directly on the pole surface. The slider moves along the transverse arm. The probe (E) is mounted on the vertical guide (F) which is fixed on the slider.

Due to the particular shape of the magnet and to the many obstacles that inhibit straight passages across the gap (like the pillars, the magnetic channels and their supports), the machine has been designed to be flexible enough to bring the probe everywhere despite these obstacles. This is achieved by mounting the components of the probe support in different configurations.

Both longitudinal and transverse movements are obtained by hydraulic actuators. The vertical positioning is done manually.

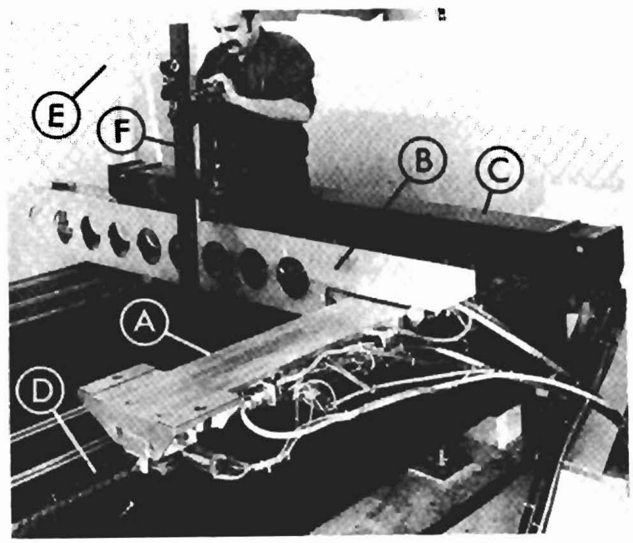

Fig. 7. The SFM machine on its testing bench.

b) The control of the machine

The machine is interfaced to the computer via a specially made control unit called "hydraulic system driver" (Fig. 8). Signals from the control computer are translated by logic circuits in this unit which in turn energize the corresponding solenoid valves. A panel labeled "hydraulic mode display" indicates continuously the states of the various actuators and cylinders.

2. The LCM Machine (Fig. 9)

This machine is composed of a granite bench (A) supporting a main carriage (B) which is allowed to move longitudinally over the whole length of the bench. A light cantilevered arm (C) supported by a column system (D) guides transversally the probe carriage (E).

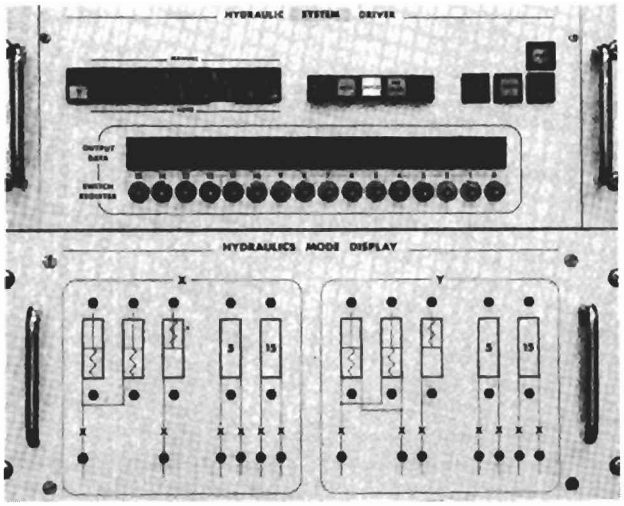

Fig. 8. The control unit and associated electronics.

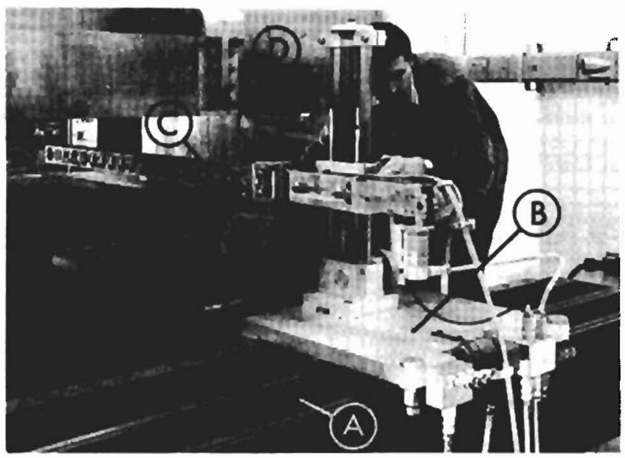

Fig. 9. The LCM machine installed for measurements.

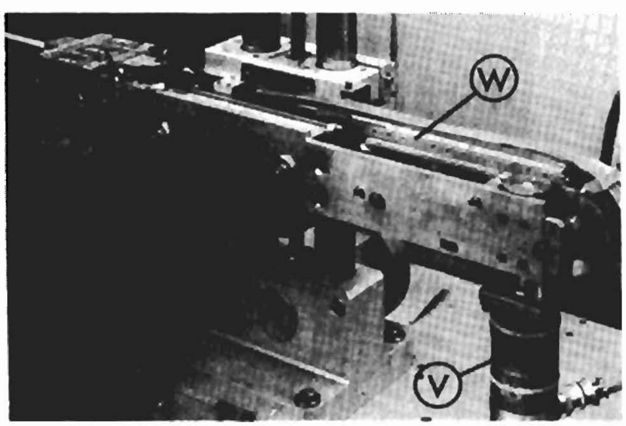

Fig. 10. The transverse system.

The displacement of the main carriage is made by a D.C. motor. The probe carriage(U) is powered by a stepping motor (V) which, after speed reduction pulls the carriage by a perforated strip (W) via a toothed wheel (Fig. 10).

A longitudinal displacement of 2800 mm and a transverse displacement of 1500 mm is possible. These movements are controlled through a unit which is linked directly to the computer. The vertical displacement (max. 500 mm) is done manually.

3. <u>The SCM/MC Machine</u>

This machine consists of a carriage which is supported and guided by two rails of L-shaped cross section which are installed on the bottom of the inside of the compensator and the magnetic channel. The carriage supports the previously described probe and is actuated in the same way as the carriage of the LCM machine.

IV. Accuracy of Measurements

The required accuracy of measurements is 1 ^{o}/oo of the maximum field value in the median plane, i.e. $\pm$ $10 \cdot 10^{-4}$ T at maximum current level in the SFM.

1. <u>Errors dueto the Electronic Equipment</u>

a) The measurement is performed through the low level analog scanner by an integrating Digital Voltmeter with an accuracy of $\pm$ 0.1 ^{o}/oo of reading, $\pm$ 0.05 ^{o}/oo of full scale and $\pm$ 1 digit, in 0.1 second. The resolution is 10 µV, equivalent to approximately $0.8 \cdot 10^{-4}$ T.

b) The Hall current is regulated to 100 mA to within 20 ppm.

c) The copper Hall plate block is temperature stabilized to within 0.1°C, equivalent to approx. $0.7 \cdot 10^{-4}$ T, at a field of 1 T.

All these errors are small compared to the required accuracy.

2. <u>Errors due to the Calibration</u>

As seen in II.2, the error due to the normal calibration is $\pm$ $0.5 \cdot 10^{-4}$ T. In the presence of a tangential field component, after correction for the planar Hall effect, the remaining error is found to be smaller than $7 \cdot 10^{-4}$ T for the maximum value of tangential field which is 0.8 T.

3. <u>Influence of the Mechanical Accuracy</u>

There are two kinds of mechanical errors: positioning and orientation. The overall mechanical accuracy in the SFM and LCM machines is within $\pm$ 0.1 mm. Therefore, with a maximum field gradient of 2.5 T/m, the error in the field measurement is $2.5 \cdot 10^{-4}$ T.

The accuracy of orientation of the probes of the SFM and LCM machines is to within 1 mrad. The orientation of the Hall plates in their probes was performed with a tangential field of 1.3 T in the two directions of the cross of the Hall plates, so that the planar Hall effect was null. This setting up was performed to within 0.3 mrad. At the maximum tangential field value, the overall mis-orientation gives an error of $8 \cdot 10^{-4}$ T.

If we consider the r.m.s. value of the combined effect of all these errors, the required accuracy is reached even in the most difficult conditions, i.e. in presence of the maximum tangential field value. Without tangential field, the accuracy is better than $3 \cdot 10^{-4}$ T.

V. The Control Computer

The digital computer shown in Fig. 11 has the following functions in the measurement system:

- to control movements of measurement probes including the reading of probe positions;
- to measure Hall-probe voltages and current;
- to calculate the magnetic field and check results for accidental errors;
- to make recording of measured data;
- to provide the operator with necessary information during measurements.

Fig. 11. The measurements control room.

1. Interfacing

The configuration of the computer system is shown in Fig. 12. The computer has a memory of 8192 words of 16 bits length. The keyboard and display terminal, the punched card reader, the paper tape reader, the paper tape punch, the fast printer and the nine-track magnetic tape system are standard peripherals connected to the computer.

The magnetic measurement devices are controlled through two TTL-compatible 16-bit duplex registers. One is connected to the SFM measuring machine and controls the length and direction of the probe movements. The second duplex register controls the other measurement machines and reads the y-coordinate of the probe position. The x-coordinate is read by 15 input bits of the SFM-register.

The operator's remote control unit is connected through a similar interface. One of the input bits will signal to the computer that a series of measurements can be started. The 7 decimal digits for the display of coordinates are serially addressed. The BCD-information is given by 4 output register bits and the address by 3 bits.

Also the low level analog scanner is connected through a 16-bit duplex register. Each solenoid of the 10 double reed relays is controlled through an amplifier from one output register bit.

The integrating digital voltmeter is connected through a 32-bit data source interface which will initiate the measurement, signal when the measurement is completed and input the BCD-reading as two 16-bit words.

The 10-bit digital to analog converter supplies the two analog voltages to the XY-recorder which may provide a simultaneous graphical recording of the measurements.

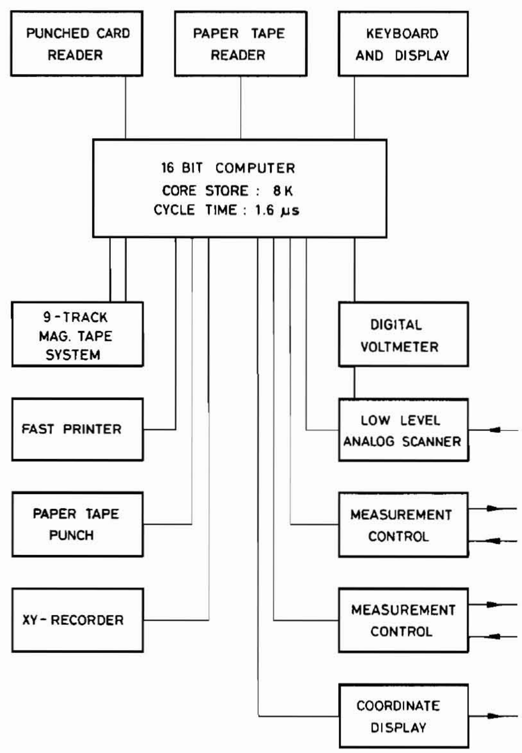

Fig. 12. Computer configuration.

2. Programming

For each of the measurement machines, an individual FORTRAN program has been written which controls the movements of the machine. The various measurement sequences and machine start conditions are introduced as run data. The data for measuring a sub-zone by the SFM machine (see section III.1) consist of:

a) A sequence of integers describing the configuration of the measuring machine.

b) Absolute coordinates for the initial position.

c) A series of numbers which describes the path along which the machine has to move.

The FORTRAN program then commands the probe movements, the analog scanner selection, the voltage measurement, the field calculation as well as the checking and printout of field values, using assembly and FORTRAN subroutines. In parallel, it allows the operator to follow the measurements by printing out the coordinates of each measured point. Together with these coordinates the field values are written on magnetic tape to be used in further data treatment. Switch options at the computer console are foreseen to enable intermediate stops and restarts in case of problems and to activate the XY-recorder or the coordinate display.

The relocatable subroutines for the controls and readings of the measurement equipment were written in assembly language. The FORTRAN programs will make use of the assembly language subroutines by usual CALL-statements.

The possibility of writing measurement programs in a high level language like FORTRAN makes the preparation of measurements fast and adds a large degree of flexibility and safety to the system.

VI. The Data Treatment

1. Permanent Data File

On the CERN main computer, permanent data files have been reserved to accommodate the measured field values in two-dimensional arrays. A file corresponds to a complete set of measured zones (median plane or three-dimensional). Initially, every array position of the file is preset by a key number which indicates that in the corresponding mesh point the field is still unknown. This file is then updated by a simple FORTRAN program which reads the magnetic tapes produced during the measurements and writes each field value to its individual array position.

The zones can be measured, therefore, one after the other in any order. Moreover, it is possible to measure afterwards in some region which need not to coincide with one of the previously measured zones and to overwrite the corresponding array locations with new data, while the rest of the array remains unchanged. This is convenient in the case when local modifications are applied to to the field, e.g. by changing the current in a compensator magnet.

2. Orbit Optimization (measurements in the median plane)

The influence of the SFM and its compensators on the circulating ISR beams is evaluated by tracking protons through the whole system and calculating the variation of beam parameters along the beam paths. These calculations are based on field measurements in the horizontal symmetry plane of the SFM where the field is purely vertical. The measurement region consists of three distinct zones which are arranged along the undisturbed beam path as shown in Fig. 13, taking advantage of the symmetry of the magnet arrangement.

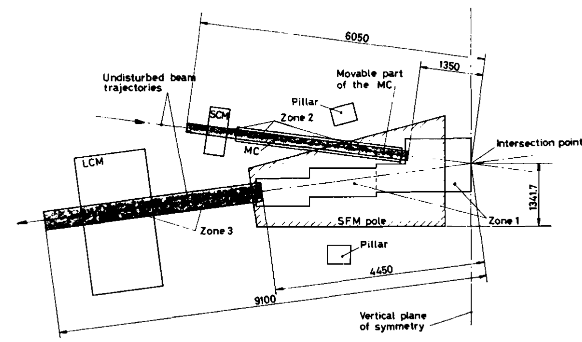

Fig. 13. Layout of measurement zones in the median plane as used for "orbit optimization".

A computer program is available to track the beam through this field and to calculate beam optical effects taking the data directly from the permanent data file. It takes into account that the measurement grid in zone 1 is not parallel to the undisturbed beam path and it is able to transpose field values from the left hand side of the system (where they were measured, see Fig. 13) to the right hand side as necessary for calculating the downstream part of the beam trajectory. After a first tracking, the program does an iterative search for an improved setting of compensator magnet currents in order to make disturbed and undisturbed beam trajectories at the ends of the magnet system identical. Because in this iteration the fields are scaled linearly with the currents, it is necessary to check the results obtained by remeasuring the field regions affected by these current modifications. After updating the permanent data file as described above, the calculations can be repeated.

3. Three-dimensional Field

To represent the three-dimensional field throughout the useful volume, a scalar magnetic potential is computed. This is possible since the volume under consideration is free of currents. From this potential, the field components in three dimensions can easily be evaluated by numerical differentiation.

Because of the symmetry of the SFM, it is sufficient to consider only a quarter of the field volume by cutting along the horizontal and vertical planesof symmetry, which have both the same constant potential.

The computer program for handling data in three dimensions is in principle organized as shown in the schematic block diagram in Fig. 14. After reading the data from the permanent file, the measured field components are integrated and will give the approximate potential distribution inside the volume and the boundary values along the surfaces. If correction of the planar Hall effect is not wanted or has already been done, the potential is smoothed out by relaxation and field components in three dimensions are computed.

For correction of the planar Hall effect, no potential relaxation is made before a first computation of the three-dimensional field. From these components, it is then possible to determine strength and azimuth of the field tangential to the Hall probe in any measured point of the grid and so to eliminate the contribution of the planar Hall effect in the measured field values. After this, a new potential approximation is established from the so corrected measurement data and smoothed out.

An example may illustrate the usefulness of the potential relaxation. Firstly, when treating not very precise data measured on the 1:5 scale SFM model with a rather primitive measuring machine, it was seen that in some isolated regions (around points where the measurement was difficult) the smoothing led to corrections up to the order of 10^{-2} T. Then, after correcting the planar Hall effect, the number of iterations necessary for a given precision was reduced, as expected, but the difference between the two final results was in the order of 10^{-3} T at maximum. This means that even the systematic error due to the not corrected planar Hall effect in the former case was largely eliminated by the application of Laplace's equation.

The final results of the three-dimensional program (potential and field components) are stored on a magnetic tape. In this form, the data will be available for use by the experimental physicists.

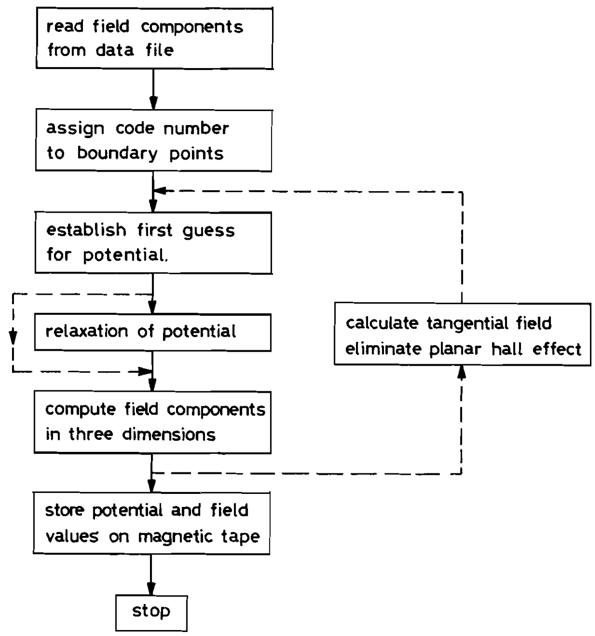

Fig. 14. Computation of the scalar magnetic potential.

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Reference

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