IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

FIELD MAPPING OF THE IUCF 200 MEV CYCLOTRON *

D.L. Friesel, J.W.D. Sinclair, B.M. Bardin, and R.E. Pollock
Indiana University Cyclotron Facility
Bloomington, Indiana

Summary

Magnetic field mapping of the Indiana main stage cyclotron is performed on a Cartesian grid using a 4 by 4 array of Hall probes. The apparatus, driven by torque motor-assisted, high-speed stepping motors, maps one eighth of the cyclotron beam area in 6 hours. Positioning accuracy is maintained by encoders attached to the stepping motor drive shafts and absolute probe locations are determined using magnetic fiducials on the magnet pole tip. The mapper is interfaced to a digital computer for automatic position control and for field data acquisition, reduction and storage. On-line data reduction includes conversion of Hall voltages to field values, allowing for individual differences in the sensitivity and non-linearity of the probes, and corrections in the fields for measured errors in the relative probe positions. Examples of the field data quality obtained are presented.

Introduction

The Indiana University 200 MeV Cyclotron is a separated sector, variable energy machine capable of accelerating particles ranging throughout the periodic table. The accelerations of such a large range of particles and energies requires one to shape the magnetic field to the relativistic profile of particle and energy involved. The ease with which the various beams can be extracted from the cyclotron depends to a large extent upon the acquisition of a complete and accurate set of magnetic field data of the cyclotron magnets and trim coils. The purpose of this report is to describe the apparatus used to obtain that set of field data.

The design of the mapping apparatus was dictated in many ways by the design of the cyclotron magnets shown in Figure 1. The separated magnets, each requiring spacers in the magnet gaps, make a 360° ρ-θ mapping system located at the machine center a practical problem. Therefore, a cartesian grid coordinate mapper is used, in which the drive elements are mounted on the top yoke of the magnet. The probes used to measure the field are placed on the end of an aluminum arm that extends from the drive system to the mid-plane of the magnet.

The area mapped out by the system consists of 1/2 a magnet, bounded by the magnet center line, and 1/2 of a valley, bounded by the valley center line, and is 1/8 of the area occupied by beam in the machine. A superposition of these partial maps gives a field representing the cyclotron configuration for calculational purposes. This procedure is valid since the magnets are located symmetrically about the machine center, and essentially behave in an identical manner when energized, particularly when driven into saturation.

An important consideration in the mapper design is the time required to obtain the field data which describes the properties of the cyclotron. To keep this time to a minimum, a grid-coordinate size must be chosen that is small enough to yield definitive information about the fields, yet keep the number of measured data points to a minimum. We employ a probe assembly consisting of 16 Hall generators located precisely on a one inch 4 x 4 cartesian grid.

* Work Supported by the National Science Foundation

Hall Probe Assembly

The development of the Hall generator over the years has made it an accurate tool for measuring magnetic fields. The probe we used is an F.W. Bell, Inc. Model BHT-910 high performance transverse Hall generator. It is a low sensitivity probe chosen for our purposes because of its high degree of linearity and low temperature coefficient. The probes have a field operating range of ±30KG, which more than covers the range of fields produced by the cyclotron magnets (17 KG Max).

Historically, one of the most troublesome aspects of using Hall probes for field measurements over long periods of time has been the large fluctuations of output Hall voltage with ambient temperature changes. The mean temperature coefficient of the Hall voltage for the BHT-910, however, is quoted as ±50 ppm/°C. At the maximum expected fields, this corresponds to a ±.85 gauss maximum error in the measured field per °C of temperature change. At lower fields, the effect becomes insignificant. The observed temperature variations in the cyclotron vault during a twenty-four hour period is typically 3 to 5°C. Thus a maximum error in the measuring field of approximately 4 gauss can be expected due to room temperature changes during a set of maps. These temperature variations generally occur over long periods of time and thus the field errors will show up as map to map differences rather than as distortions of a given map. No attempt was made to correct the output voltage of the Hall generators for temperature variations, nor are they mounted in a temperature controlled environment.

The sixteen Hall probes are mounted on a .125 inch thick fiberglass board. The probes are powered in series by a 15 volt, 100 mA constant current supply. The power distribution network and linearizing resistors for the probes are also mounted on this board. The required position accuracy of the probes on the one inch grid is of the order of ±.005 inches. The problem of locating the probe precisely on the one inch grid amounts to locating the center of the active area of each Hall generator. This is done by producing a local field "bump" in an otherwise uniform magnetic field. The field "bump", roughly Gaussian in shape and having a FWHM of 0.16 inches, is generated by an iron pin (called a fiducial pin) 1/16th inch in diameter by 1/16th inch long placed on one pole tip. The center of the Hall probe active area is determined by finding the point which gives the maximum Hall voltage output, corresponding to placing the center of the active area of the probe at the maximum field point. Using this technique, the probe centers were located on the desired grid with a precision of ±.005 inches, and their positions are known with an accuracy of ±.001 inches.

Hall Probe Calibrations

The quantity measured by the Hall generator is the intensity of the magnetic field, B. The sensitivity of the Model BHT-910 probes are about 0.8μV/G ± 30% and are generally slowly varying functions of the field intensity. The quoted linearity is ±0.1% and is about a factor of 10 larger than required to be used without corrections over the range of fields measured in the cyclotron. In addition, the zero field output voltage varies from probe to probe and must also be determined. Because of their low sensitivity, the Hall output voltage of the probes are measured with a precision integrating digital voltmeter. The DVM has an accuracy of ± 1 microvolt, or at .8μV/G, a field measuring accuracy of ± 1.2 gauss.

The calibrations of the Hall probes were carried out in the main cyclotron magnet. This was done so that the effects of the magnet warming when excited and of the Hall plate warming when powered would be inherent in the calibrations. The probes were calibrated against a Spectro-Magnetics 5300 NMR digital Gauss Meter which has an operating range of from 2 to 20 K Gauss and a field measuring accuracy of 0.01%. The mapper drive system was used to position each probe in series at a point in the magnet gap least affected by saturation. The probes were calibrated at field intervals of approximately 1500 Gauss from 7 K Gauss to 16.75 K Gauss. The data at each point were normalized by the output of another Hall probe, fixed in position in the magnet to monitor fluctuations in the field.

The zero field output voltage of the probes was measured by placing the probes in a region of zero magnetic field and measuring the output voltage. These voltages were also normalized to the input Hall current of 100 mA.

The Hall constant γ_H was found to vary smoothly by as much as $\pm 0.15\%$ over the range of fields produced by the cyclotron magnets. In order to interpolate between the measured values of γ_H, the data for each probe were fit with a quadratic of the form;

$$\gamma_{Hn} = A_n + B_n V_{Hn} + C_n V_{Hn}^2$$

The value of A_n is γ_{Hn} to first order, while B_n and C_n are a measure of the non-linearity of the probe sensitivity. B_n was found to be negligibly small in all instances, while C_n was significant for most probes. This quadratic equation was used to determine the Hall constant at each value of the output voltage measured during a normal field mapping sequence.

Mapper Mechanical Design

The x-y coordinate system of the mapping apparatus is defined by a pair of crossed lathes whose drive mechanisms have been removed. The larger lathe (9 ft.) is located on top of the yoke of the magnet and is aligned parallel to the magnet centerline, defined as the x axis. The smaller (7 ft.) lathe is mounted on the saddle of this lathe and is aligned perpendicularly to the magnet center line, defined as the y axis. An 8" diameter aluminum arm is mounted on the saddle of the y axis lathe and extends 15.5 feet down to the midplane of the magnet. The apparatus is illustrated in Figure 1.

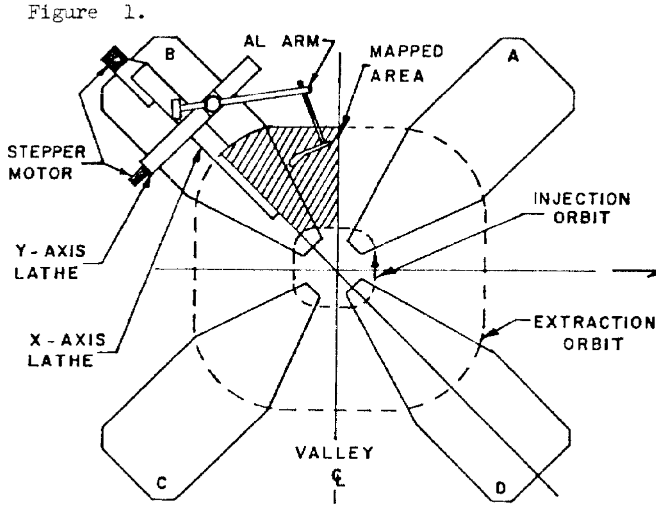

Figure 1

The drive motors and gear boxes for the lathes have been replaced with high-speed stepping motors, coupled directly to the worm gear which drives the lathe saddles. Since the output torque of the stepping motor is inversely proportional to the input pulse rate, the maximum rate of linear motion is determined by the torque required to move the lathe saddle. For the X axis, this occurs at 500 pulses per second or at a linear velocity of 0.07 inches per second. A smooth acceleration is required to go from a standing stop to the desired velocity because of the minimum response time of the stepping motor and to prevent vibration of the boom. The time required to move the boom 4" along the X axis, including a smooth acceleration and deceleration, is 60 seconds.

The y axis saddle is driven by a smaller stepping motor coupled directly with the output of a torque motor. The output torque of the motor is slightly less than that of the stepping motor, so that the stepping motor cannot be over-ridden. This step/torque motor combination is capable of driving the y axis saddle at a linear velocity of 0.30 inches /Sec. Thus, a 4" move along this axis, including a smooth acceleration, is accomplished in approximately 16 seconds.

The position sensing is monitored by optical incremental shaft angle encoders coupled directly to the output shafts of the stepping motors. The encoders have a resolution of 256 pulses per revolution, and are direction sensing. The outputs of the encoders are fed into 20 bit up-down counters for overall position sensing. The position resolution of the system using these encoders is 0.13×10^{-3} inches/count and 0.065×10^{-3} inches/count for the x and y axes respectively.

Computer Control

The mapping hardware is interfaced to the Datacraft 6024/1 acquisition computer for automatic control. The computer is a disk-oriented system containing a fully operational disk monitor. Hence, the mapping programs are written in a sub-routine format and are stored on the disk. A general Fortran "scanning" program is then used to access the sub-routines as required to perform the various field maps. Under computer control, the motions of the probe, data acquisition, reduction and storage all occur automatically. The outputs of the up-down counters are monitored for continuous position control. The information as to where to "scan" is contained in a data file called a "drive" file. Therefore, different areas can be mapped by the construction of different drive files. Such problems as the removal of backlash in the gears of the drive mechanism, lathe stall detection and restart, the rate of acceleration and deceleration of the axes and the conversion of Hall voltages to field values, including corrections for the non-linearity of the Hall probe outputs, misalignment voltages and fluctuations in the fixed Hall probe or the Hall current, are all conveniently handled on-line via the computer. In addition, the scan program is put into a hold, or wait state, if large changes in the field are detected by the fixed probe (i.e. if the magnet power supply should go out of regulation or shut off) or if the lathe apparatus fails for any reason. When the problem is corrected, the scan may be continued from that point. The field data are transferred to magnetic tape for storage and future use.

The computer is also used to automatically "seek" the maximum field produced by an iron fiducial. The program sweeps Hall probe in .01 inch steps across the fiducial pin from -.25 to +.25 inches, recording the Hall voltage at each step. The resulting peak is fit with a gaussian, whose centroid is determined. Two iterations of this process in both the x and y axis give the location of the fiducial pin (and hence the probe assembly) which is always reproducible to ±.001 inches.

The precise alignment and the location of the apparatus relative to the magnet pole tip was done in two steps. First, the x-y grid coordinate system defined by the lathes was aligned with one axis parallel to the magnet center line. The 16 probe assembly was then aligned to overlap that grid. The key to these alignment procedures is the use of a set of iron fiducials on the magnet pole tip at precisely known locations relative to the machine center and the magnet pole edges. The x-axis lathe was aligned parallel to the magnet center line using the fiducial pins placed at 33.5 inch and 133.5 inch distances from the machine center. Using the fiducial seek programs, the x axis lathe was located parallel to the axis defined by the fiducials to .002" over the 100-inch distance between them. The y axis lathe was aligned to be perpendicular to the magnet center line using a right triangle of 20 inches on a side with fiducial pins located precisely at the corners. One side of the triangle was aligned parallel to the x axis, and the y axis was adjusted until it was parallel to the other side to within ±.001 inches. During the alignment of the y axis, however, the distance between the fiducials measured mechanically and by the mapping apparatus differed by .040 inches in 20. This discrepancy was caused by a rotation of the y axis lathe about the x axis when the 300 lb. boom moved from one end to the other along the y axis. Because of the 15.5 ft. moment arm, rotations of a fraction of a degree result in large horizontal deflections at the probe tip. The y axis lathe was also found to "droop" about its point of support on the x axis saddle. Both effects were of the same order of magnitude, and the amount of rotation varied slightly as a function of its position along the x-axis. The errors caused by these effects were mapped as a function of the x and y location in the grid and two data files, ΔX (x,y) and ΔY (x,y), were compiled and stored on the computer disc. Another subroutine was written into the "scan" program which accessed these data files and made corrections for the rotations during each move. The error routine was checked against the right angle fiducial plate at various locations in the magnet. From these data, an x or y axis position accuracy of no better than ± .005 inches can be claimed for the total area available to the mapper. Following the alignment of the lathes, the probe assembly was aligned to overlap that grid. Using the 4 corner probes, the 1-inch rectangular grid of the probe assembly was positioned to overlap the grid defined by the lathes to within .028 degrees, the accuracy obtainable with the fiducial seeking program.

Concluding Remarks

There are 462 moves per 1/8 MAP, or at 16 field points per move, 7400 data points per scan. At each grid point, the 16 Hall voltages are read, along with the input Hall current, the magnet current shunt voltage, and the fixed Hall probe voltage. The total time required for a full 1/8 map is 5 hours and 45 minutes. With this system usually 3 maps per day were made and when necessary, even 4 maps per day were obtained. When the scan is complete, it comes back to the fiducial at the front of the pole tip to within .005 inches in both axes.

The precision of the probe to probe calibrations are verified by a close scrutiny of the field data in the flat part of the field, and in the valleys. In the valleys, where the field is approximately zero, probe to probe differences were less than a gauss. In the hills, the probe to probe differences were about ±2 gauss. The accuracy and sensitivities and probes are amply demonstrated in the high field regions of the pole tips by their being able to see the machining errors in the pole tips. The pole tips were machined with 9" diameter mill bits which left grooves in the poles having a depth of about .0015 inches. Thus, the pole tip gap varies with a regular longitudinal amplitude of .003 inches. This is 0.1 percent of the total gap of 3 inches. At an average field of 7 Kg in the gap, these machining errors cause the magnitude of the field in the gap to vary with an amplitude of 7 gauss at a period of 9 inches. These field fluctuations show up clearly in the field data, as shown in Figure 2. Another sensitive test of the probe to probe calibration is to look at the derivatives of the field data. Oscillations in the derivatives having a periodicity of 4 inches are a result of probe calibration differences. Examples of this oscillation for the probes along the x axis are given in Figure 3. Figure 4 is a photograph of typical field data as displayed on the scope of the Datacraft computer. Note that in all of these data, the 4 x 4 array of the 16 probe assembly cannot be observed.

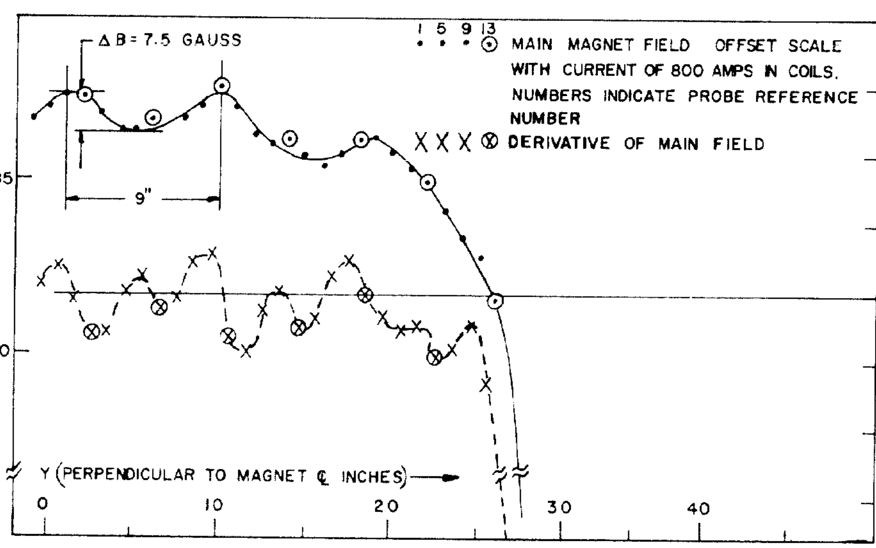

Figure 2

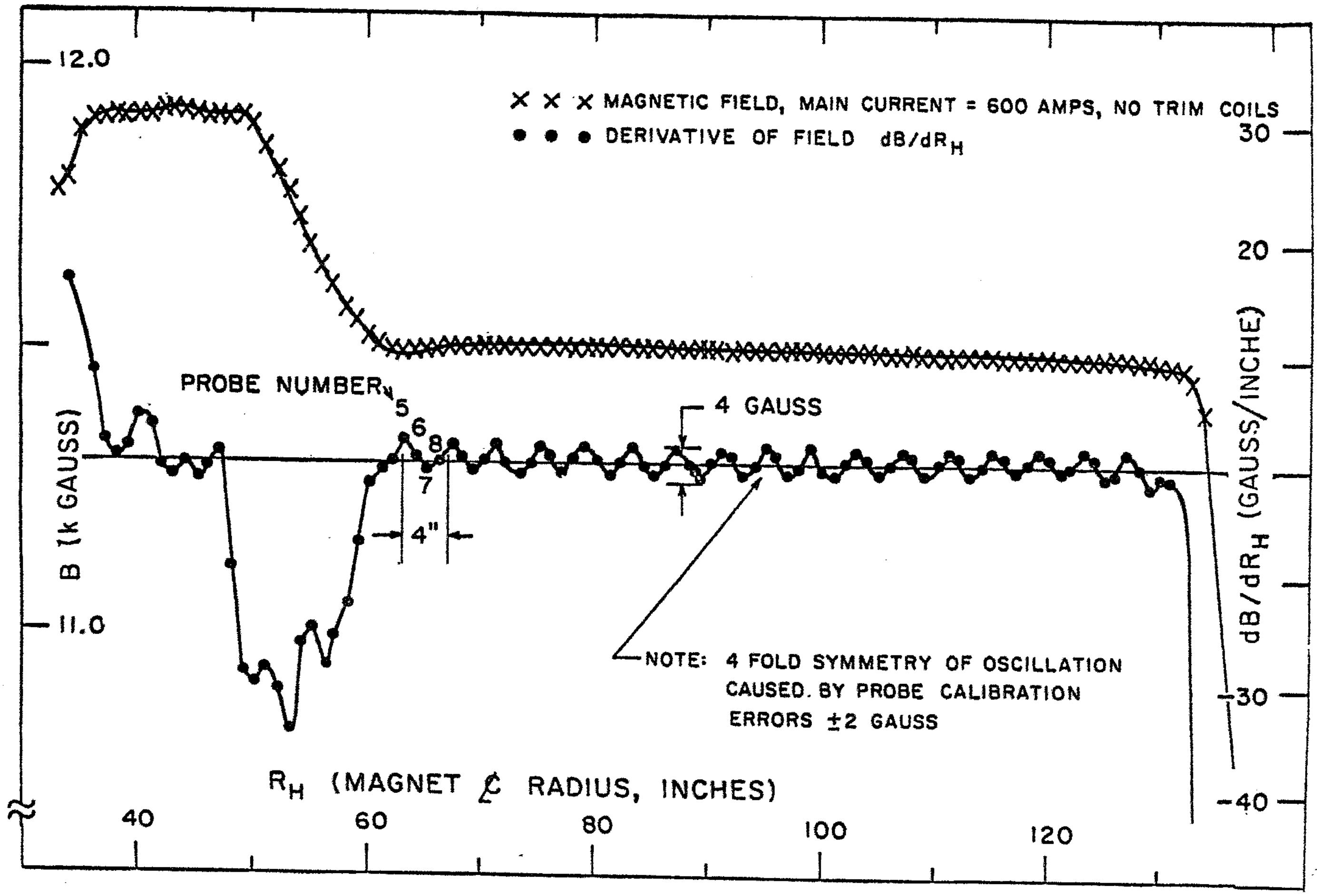

Figure 3

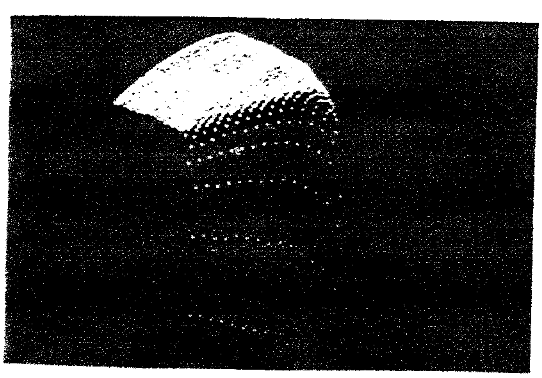

Figure 4a

A three-dimensional oscilloscope plot of field data showing oscillations in magnet field caused by pole tip machining grooves. Main current is 600 Amps, maximum field is 13.8 Kgauss. Plot is on an off-set scale showing the field from 13.0 to 13.8 Kgauss. The data shown in figure 2 was plotted from this same field map.

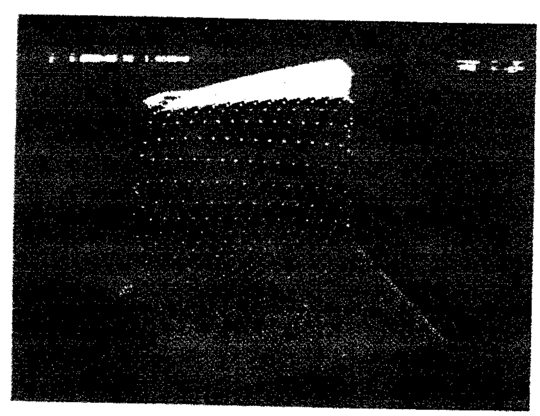

Figure 4b

Oscilloscope plot of the same data on a scale of 0 to 14 Kgauss max. Figure 3 is a hill center line section of this data.