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THE TEXAS A & M UNIVERSITY 88-INCH SECTOR-FOCUSED CYCLOTRON

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ABSTRACT

This paper describes the magnetic measurements program for the new sector-focused cyclotron at Texas A & M University. In preliminary measurements a simple analog system was used to measure symmetry distortions in the magnetic field. The main portion of the test program employed the Lawrence Radiation Laboratory's Rapid Mapper digital data-acquisition system in which a search coil and integrator are used to measure the magnetic field. In a period of two weeks 3/4 million measurements were made. In this paper the authors discuss the planning and preparation for these measurements, and the steps in data gathering and data analysis. A cost analysis is presented.

Initial results indicate that the TAMVEC magnetic field is of very good quality and compares closely to the field of the LRL 88-inch cyclotron, a near twin of TAMVEC.

Features of the Rapid Mapper system which were particularly appropriate for this measuring task are discussed. They include: a peak data-logging rate of 5 measurements per second; a data resolution of less than 1 gauss; a measuring uncertainty of less than 3 gauss; extensive data-identification features; and versatile computer programs for data analysis.

INTRODUCTION

In collaboration with the Lawrence Radiation Laboratory (LRL), Texas A & M University has recently completed magnetic measurements of a new 88-inch variable-energy sector-focused cyclotron (TAMVEC) at College Station, Texas. Magnetically the cyclotron is virtually identical to the 88-inch cyclotron at LRL, a machine that has been in successful operation since 1961.

During a 2-week period in May 1967, 3/4 million magnetic field measurements were made in the Texas cyclotron by use of the LRL Rapid Mapper system.[1] The digital measurements consisted of detailed "maps" of the mid-gap field within a 9-foot-diameter circle centered at the magnet's origin. These measurements were for the purpose of determining the separate and combined effects of the main coils, the 17 pairs of circular trimming coils (trim coils), and the five sets of harmonics-correcting valley coils at various central field levels in the range 0 to 19 kilogauss.

Preliminary analog measurements were made in February 1967 to test the quality of the main coil field prior to the installation of trim coils and valley coils. In these tests the magnitude of the magnetic first harmonic was measured at selected radii and field levels with a simple analog system.[2]

This paper describes the preparations for the analog and digital measurements, and gives details of the measuring procedures, preliminary results, and conclusions on the measuring system and the test program.

PRELIMINARY WORK

Background

In 1965 a decision was made to construct at Texas A & M University a slightly modified version of the LRL 88-inch cyclotron. Arrangements were made with LRL to provide engineering and technical assistance. In February 1966 a meeting was held with representatives of Texas A & M, Bechtel Engineering Corporation, and LRL to discuss two phases of magnetic field measurements. The following program was proposed.

1. In phase I, following the assembly of the magnet core and main coils, the quality of the basic magnet structure was to be evaluated by measuring the first harmonic of the magnetic field, by use of an array of three search coils placed 120 deg apart in the field. (Later simplified to a two-coil array.)
2. In phase II, following installation of the valley coils and trim coils, the LRL Rapid-Mapper data-acquisition system was to be used to obtain digital data for use with orbit codes and to compare the Texas cyclotron with its counterpart at LRL.
3. Positioning systems were to be fabricated at LRL for use in phases I and II.

In addition, LRL was to provide engineering and technical assistance in preparation of the test plan, in modifications of the LRL data-processing programs, and in operation and maintenance of the measurement system at Texas A & M.

Measurement Preparations

The organization of the LRL 88-inch cyclotron measuring program in 1961 was used as a guide in planning the measurement program for TAMVEC. Measurements were planned for the same main-coil, valley-coil, and trim-coil levels to allow direct comparison of the two machines. Some simplifications in the program were made because of the similarity between the two cyclotrons. However, with the high-speed measuring system used it was expedient to make more measurements than were made in the 1961 Berkeley program. To assist in performing the measurements, check lists were prepared in advance in which step-by-step instructions were given for operating the system and setting control switches for each type of measurement planned.

It was felt that data processing would best be done at Texas A & M, therefore LRL supplied copies of the LRL 88-inch data together with Magnet Testing Data Processing programs[3] and 88-inch-data-analysis programs. These programs were modified to run on Texas A & M's IBM 7094 computer.

Mechanical Preparations

Two azimuthal probe-positioning carriages were designed to work with the aluminum indexing disk from the 1961 LRL cyclotron measuring program. The disk is 8 ft in diameter and 1 in. thick, and has 240 equally spaced dowel pins at a 46-in. radius from a centering hole. A 2-in. -diameter post passed through this hole and was attached to the magnet pole tip. The carriages pivoted about this post and were supported by wheels near the indexing pins. A three-tooth "gear" engaged the indexing pins and was used for position readout in phase I and for position control during phase II.

The phase I carriage, Fig. 1, positioned two search coils 120 deg apart, in holders placed at selected radii in holes in two radial arms.

The phase II carriage assembly, Figs. 2 and 3, positioned the Rapid Mapper "guide tube" across the center of the magnet. Azimuthal indexing was by stepping motor and cogged belt drive of the three-tooth gear. This mechanism positioned the guide tube in azimuth with an uncertainty of less than 1×10^{-4} radians.

Preparations at Texas A & M

Preparations at TAMVEC consisted of calibrating the various power supplies, positioning the indexing disk in the magnet, and checking the computer programs with sample data prepared with the Rapid Mapper. Special attention was given to checking the power supplies for regulation, ripple, and current calibration. Each power supply was run for at least 72 hours prior to the measurements. The indexing disk was positioned horizontally to within 0.0035 in. of the geometric center of the cyclotron and vertically so as to place the search coils within 0.010 in. of the median plane of the cyclotron.

The computer programs were run by using sample data maps furnished by LRL. These maps simulated actual cyclotron data and allowed the checking of tape formats.

PHASE I MEASUREMENTS

As stated earlier, the first phase of magnetic measurements was primarily for the purpose of measuring the first harmonic effects resulting from deviations from threefold symmetry in the magnetic field produced by the main coils and by the position of the ion source mechanism. An analog system was chosen for phase I primarily because of limited availability of the Rapid Mapper. The analog method was very appropriate to the studies in this phase and, in fact, can be more convenient than a digital method in determining the effect of the ion-source position on the first harmonic.

A complete description of the theory and use of this system is given elsewhere.[2] Very briefly, the method is as follows: Two identical search coils, each with a turns area of about 10^5 cm^2, are placed on a fixture so that they are at the same radius but 120 deg apart in the magnetic field. As the fixture is rotated about the origin, the integrated difference signal from the two coils contains only terms in $A_1, A_2, A_4, A_5, A_7, A_8, \cdots$ from the field expansion $B(R, \theta) = A_0(R) + A_1(R)\cos(\theta - \alpha_1) + A_2(R)\cos(2\theta - \alpha_2) + A_3(R)\cos(3\theta - \alpha_3) + \cdots$. In practice A_3, A_6, A_9, $\cdots$ terms also appear, but their signals are greatly attenuated in amplitude. For this reason it is possible to resolve A_1 and A_2 amplitudes of a few gauss when A_3 has an amplitude of 3000 gauss. The reference also describes a method for graphically recording the data in such a way that the terms A_1 and A_2 can be directly evaluated with a resolution of 2 gauss.

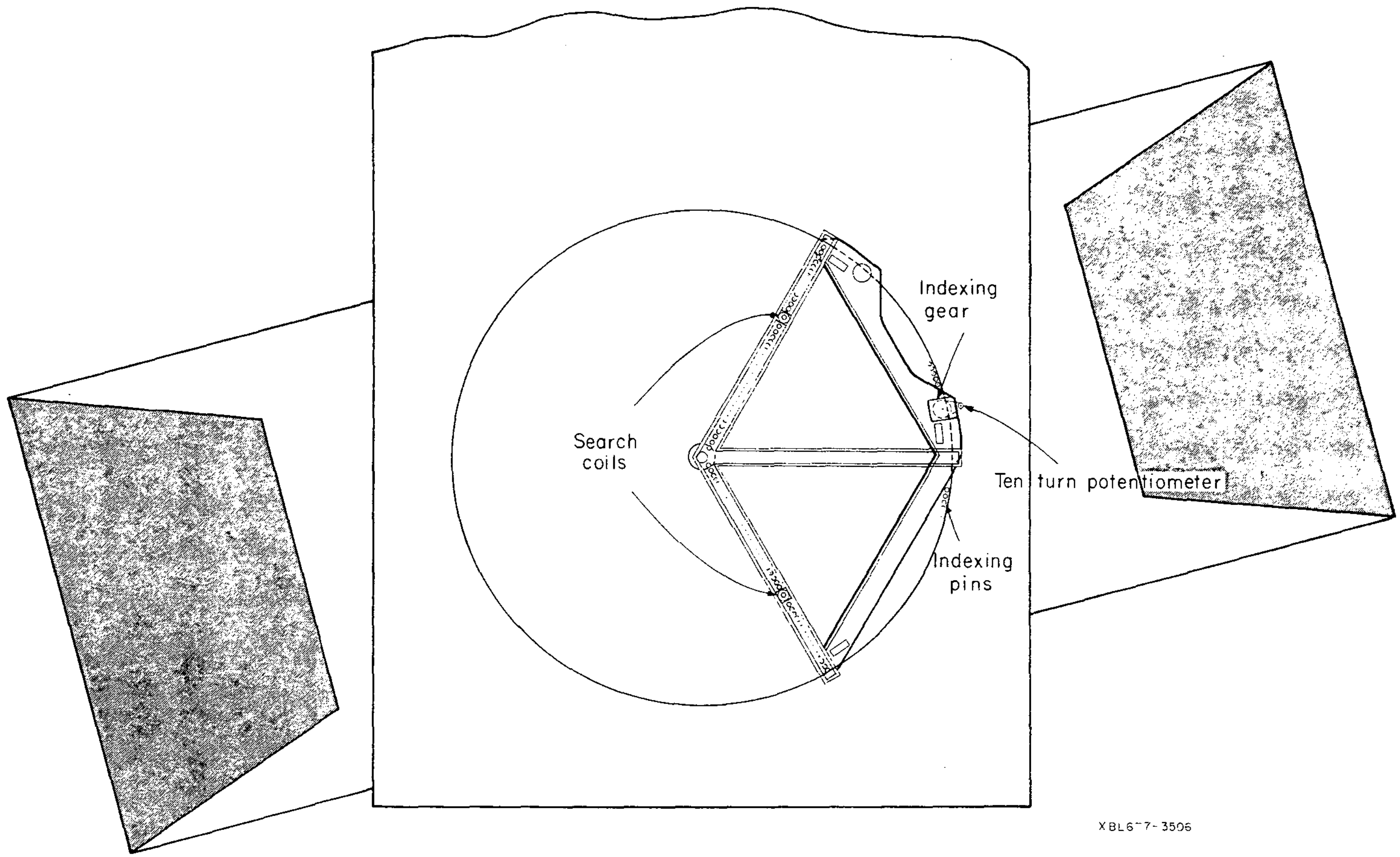

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Fig. 1. Phase I positioning fixture.

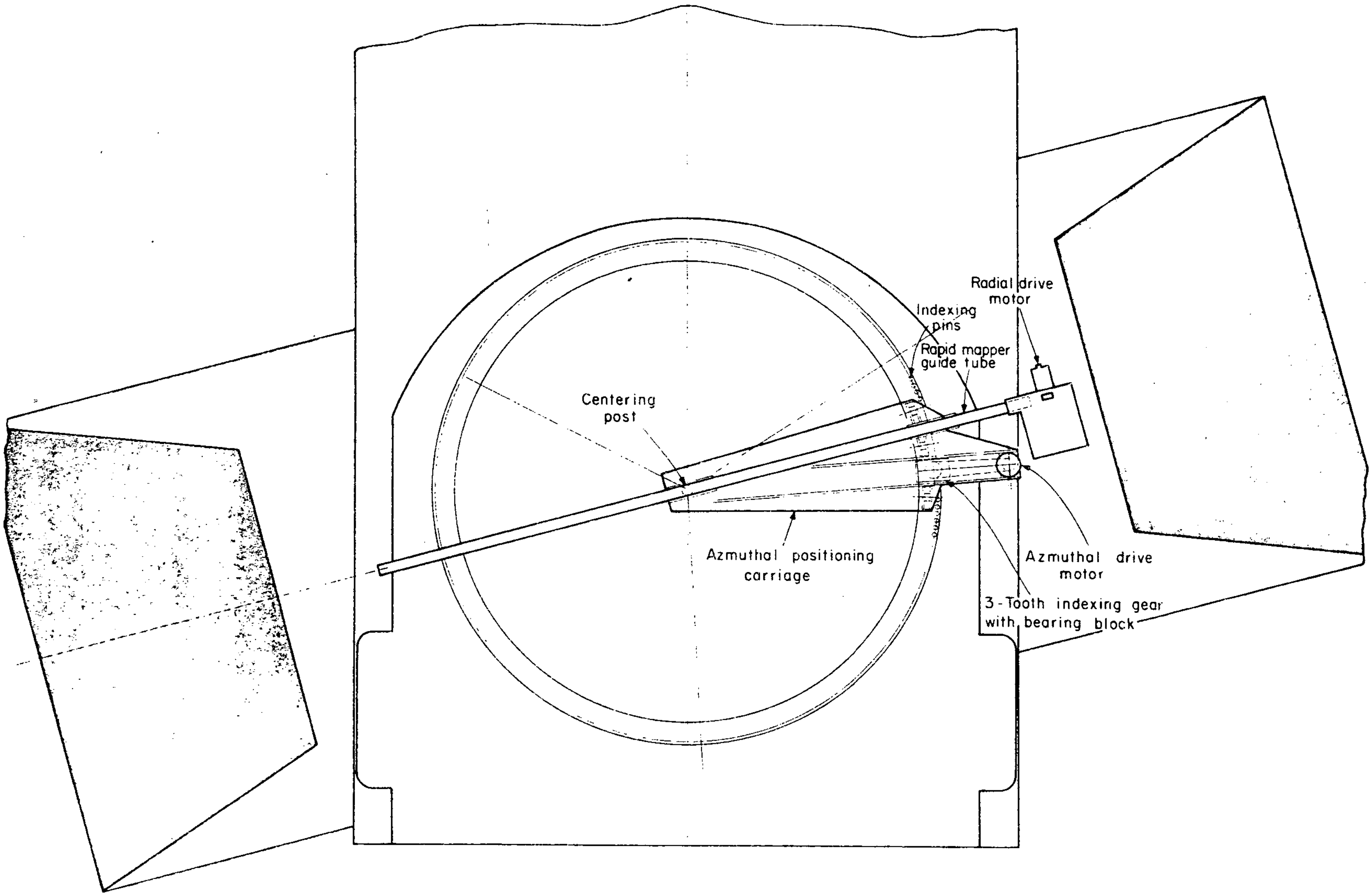

Fig. 2. Phase II azimuthal positioning carriage with Rapid Mapper guide tube.

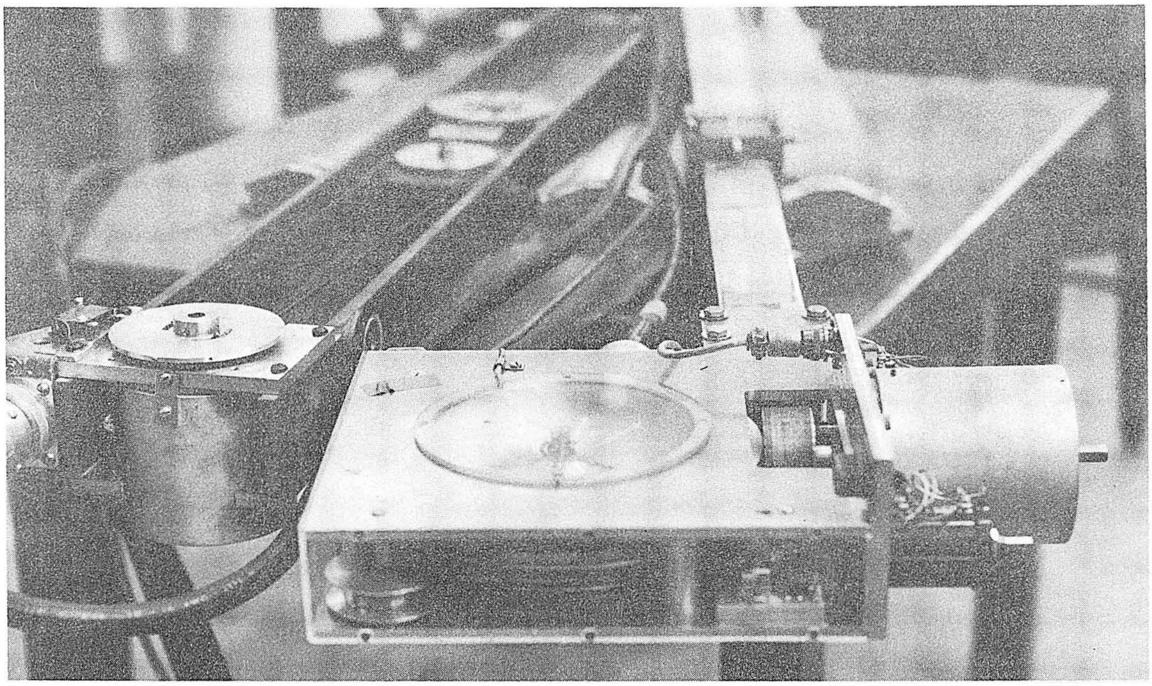

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Fig. 3. Stepping-motor drive section of the Phase II positioning carriage assembly.

For this method to be capable of good resolution it is very important that the two arms be exactly 120 deg apart and that they intersect at R = 0. In a last-minute rush to complete fabrication of the fixture, an assembly error occurred whereby the two arms were set 119.5 deg apart and one arm was displaced 0.03 sec radially. The resulting A_3 "noise" signal was greater than 20 gauss in amplitude. To get sufficient resolution of A_1 without a complex harmonic analysis it was necessary to adjust one of the search coils. With each change to a new radius of measurement the search coil position was readjusted until the A_3 noise signal was less than 2 gauss. Despite this handicap the device proved its worth by providing directly interpretable graphs that quickly revealed magnetic anomalies and asymmetries of small magnitude.

Harmonic measurements were made at seven radii for each of six values of main coil current. The first harmonic did not exceed 5 gauss at any of the radii or current levels checked. Furthermore, in comparing the first and second harmonics at a radius of 44 in. with corresponding LRL data, it was decided that no shims were needed to correct for main-coil lead effects, as had been necessary in the LRL cyclotron.

PHASE II MEASURING PROGRAM

The purposes of the Phase II measurements were (a) to evaluate beam-disturbing magnetic-field harmonics at various field levels, when the main coils were energized by themselves, and when energized in combination with trim coils to produce isochronous fields, (b) to measure the harmonic effects of five sets of harmonic-correcting valley coils, and (c) to gather an adequate body of data on main-coil and trim-coil effects so that isochronous fields may be established for the entire range of energies and particles within the accelerating capability of the cyclotron.

To meet these goals the following types of data were collected: three-sector (360 deg) and one-sector (120 deg) maps of the main-coil effect, measurements of the trim-coil and the valley-coil effects, and measurements of the combined effects of the main coils and the 17 trim-coil pairs ("Grand Tests").

The three-sector main-coil effect maps were made at six field levels, called principal field levels. These maps provided data for harmonic analysis, and were used to establish that the one-sector main-coil data accurately represent the three-sector averages. The one-sector maps of the main-coil effect were made at 30 additional field levels so that intermediate field level maps could be calculated with an interpolation error of less than 0.1% of the maximum field.

Measurements of trim-coil and valley-coil effects, were made only at the principal field levels. To separate these relatively small effects from the large effect produced by the main coils, measurements were made with trim-coil pairs or valley-coil sets operated first in one polarity and then in reverse polarity. The difference between the two sets of measurements was the effect being evaluated.

A significant saving in effort resulted from an examination of the 1961 LRL measurements of trim-coil effects. It was found that the azimuthally averaged effect could be accurately approximated by measuring the effect at two suitably chosen azimuths 180 deg apart. The error introduced was never more than 2% of the maximum trim-coil effect. A single measuring run across the magnet centers was sufficient for each current configuration.

In the measurement of valley-coil effects the 1961 LRL procedure was followed.[4] A valley-coil set is composed of three pairs of coils symmetrically located in the valleys of the upper and lower pole tips. There are five sets numbered in order of increasing radius in the magnet. Each pair of coils in a set is separately energized. A current distribution was chosen that produced a first harmonic effect of desired phase and amplitude without altering the azimuthally average field, namely, +A in one pair and -1/2 A in each of the other two pairs in each set. The harmonic effects are sufficiently localized in radius so that the effects of sets 1 and 4 and of sets 2 and 5 could be measured at the same time. The effect of set 3 was measured separately.

Tests of the combined effect of the main coils and the 17 trim coils simultaneously energized to produce an isochronized field were given the name "Grand Tests." The purposes of these tests were to study harmonic content of the resulting field and to study superposition errors when large changes in field profile are produced by many trim coils. The TAMVEC Grand Tests duplicated Grand Tests at LRL.

Table I summarizes the Phase II measurements.

Table I. Phase II magnetic measurements.

Types of measurement	Azimuthal range (deg)	Azimuthal increment (deg)	Levels measured	Number of measurements made
Three-sector main-coil tests	360	3	6	158 000
One-sector main-coil tests	120	3	30	255 000
Trim-coil tests	(see text)		6	45 000
Valley-coil harmonic tests	360	15	6	190 000
Grand tests	360	3	5	132 000
		Total measurements		780 000

Three weeks of two-shift operation were required to complete the phase II measuring program. Most of the first week was used for setup, alignment, and debugging. The remaining time was used for data collecting, and proceeded with only minor interruptions.

PHASE II MEASURING PROCEDURE

The measuring procedure was largely dictated by the operation of the Rapid Mapper, which is described in a separate report.[1] In essence, the system positions a field-sensing probe and records digital data from the probe and other inputs for later processing by a computer. The field-sensing mechanism is a search coil and integrator.[5] In each data run the search coil travels the length of a 2-in.-square aluminum guide tube and returns to its starting point. Every 1.0032 in. the search coil pauses and its integrated output is digitized. Measurements are made during both directions of travel so that each point is measured twice. Performing these measurements swiftly (at 5 readings per second) reduces measuring errors due to integrator drift. Because of this speed, and because readings at corresponding positions from the two halves of each run are compared and averaged, the measuring error at each radial position is less than 2 gauss relative to the measurement at the magnet center. A run of 219 measurements takes 45 seconds.

To measure the TAMVEC field we chose to mount the guide tube across the center of the magnet. Thus, for a radial run of 109 in. the search coil traveled from R = -55 to R = +54 and back again. The original plan was to use both the negative-radii and positive-radii portions of runs so as to reduce the azimuthal range needed for most of the measurements. Because of a slight bend in the guide tube this measuring plan proved less practical than simply taking twice as much data and using the negative-radii values only as a check of radial registration with respect to the origin. An exception to this was in the measurement of trim-coil effects at two azimuths 180 deg apart. For these measurements runs across center were used.

The Rapid Mapper measures field magnitudes relative to the field at the starting point of each run. For the TAMVEC measurements we modified the data-processing program CERTFY to "level" each run to the field value at the magnet's center, a point common to all runs of a map. This value was established by the reading of an NMR probe placed over the center of a hill, and one run of the map that passed through the NMR location.

PHASE II DATA PROCESSING

The plan for computer processing of the magnetic data consisted of two parts: first, verification of the raw data and harmonic and symmetry analysis of the main field levels, and second, manipulation of the various main-field and trim-coil data into a format for convenient entry into the cyclotron development program, CYDE, and for direct comparison with the LRL data. The first part was accomplished concurrent with the data taking. The second part was started after the completion of the measurements, and is being continued at the time of this writing.

A flow chart of the concurrent data processing is shown in Fig. 4. Data taken by the Rapid Mapper were written on a tape called "the mapper tape." The mapper tape is IBM-compatible and is written at 200-bpi density. After a day's data taking was completed the mapper tape was processed by the 6600-7094 converter program, CONVERTER, and the TAMDOB program. The printed results of each map were then visually inspected for data-recording errors or omissions and for data validity. The processing to this point was done prior to starting the next day's data taking. In the event an uncorrectable error was detected the affected map was retaken the next day. This short turnaround time proved its worth on several occasions.

As the next step, the data tape was processed by the program CERTFY, which produced the auxiliary tape and printed results of the normalizing and leveling operations performed.

The harmonic and symmetry options of program POLAR were used to analyze the data on the auxiliary tapes and print the results.

The flow chart of the second part, Fig. 5, outlines the various steps that are being employed to prepare the data from the orbit codes. Even though this part has not been completed, preliminary results indicate close agreement with the LRL cyclotron.

Detailed descriptions of the computer programs used are given elsewhere.[8] A brief description of these programs (with additional references where applicable) follows:

1401 Programs. Two 1401 programs were written at Texas A & M: CONVERTER for formatting the Rapid Mapper tape for direct entry in the 7094, and TAMDOB for listing of the raw data tape for visual inspection.

CERTFY.[3] The primary purposes of CERTFY are to reduce the effect of random and systematic errors, to provide matrix-formatted printouts showing data quality, and to produce an output tape for subsequent processing. Measured data were also leveled in CERTFY to an NMR field reading made at the start of each map.

FILMER.[3] The purpose of this program is to combine the contents of one or more input tapes while editing the data by deleting, adding, or replacing blocks of data.

POLAR. The purposes of POLAR are to transform the data from the measuring coordinate system to the magnet's coordinate system and to perform computations pertinent to cyclotron data. The computations include symmetry computations, harmonic analysis, evaluation of trim-coil effects, and calculation of the azimuthally averaged field at each radius.

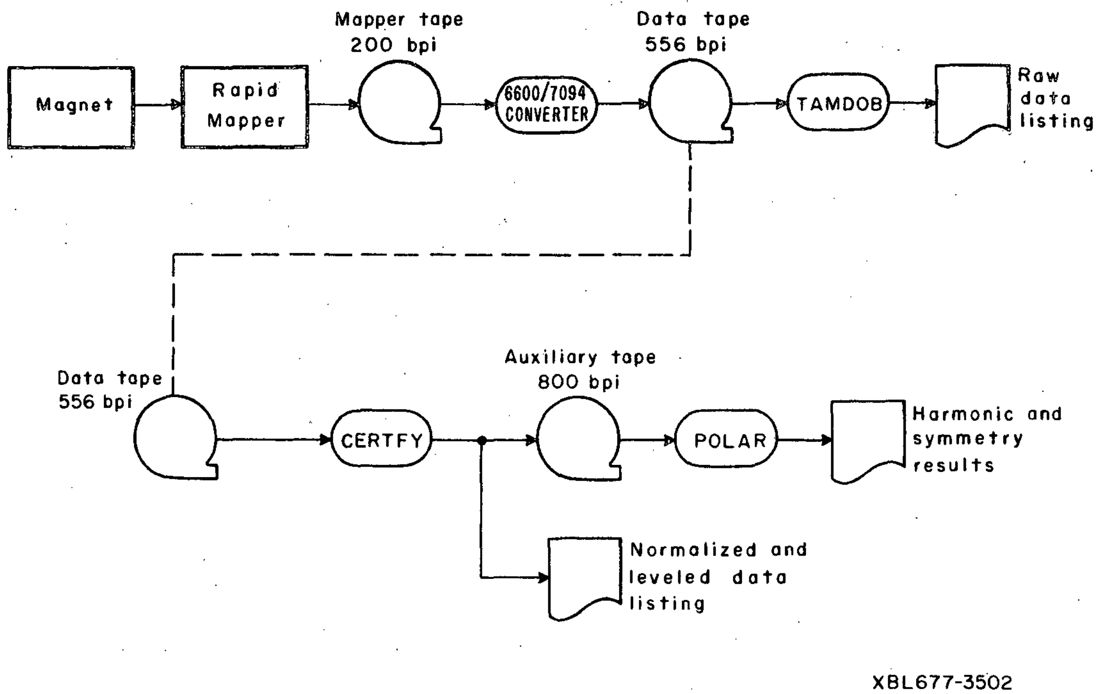

Fig. 4. Flow chart of data processing during Phase II measurements.

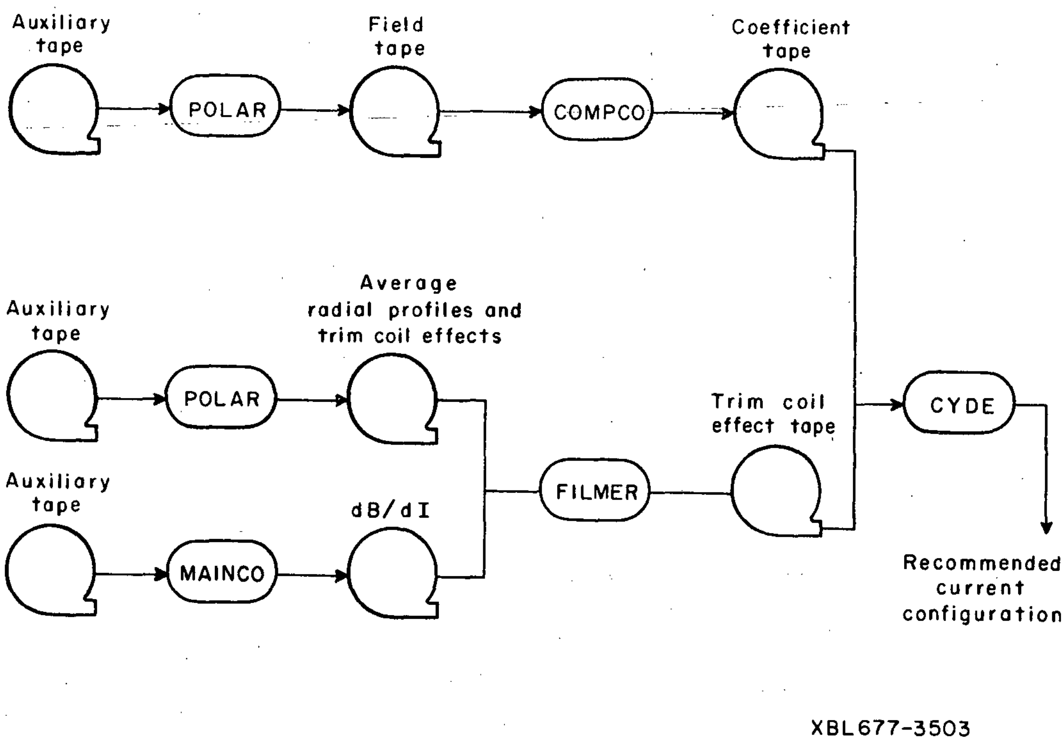

Fig. 5. Flow chart of data processing to produce isocronized field.

COMPCO.[7] This program is used to compute coefficients from which a map can be generated at any magnet current. The method used is to represent the magnetic field at each coordinate pair (r, θ) by a polynomial in I (magnet current) over localized regions of I, and to store the polynomial coefficients in a prescribed format on magnetic tape used as an input to CYDE.

MAINCO. This program computes dB/dI of the azimuthally averaged main coil magnetic field at the six principal field levels. These values are combined with the azimuthally averaged main field values and the trim coil effects at the six principal field levels to produce the trim-coil effect tape, a second input to CYDE.

CYDE.[6] This collection of Fortran II Cyclotron Development codes combines the measured effects of the main coils and the 17 trim-coil pairs to determine an isochronous field while satisfying certain parameter limits.

PHASE II RESULTS

Harmonic analysis of the digital measurements in Phase II confirmed the analog results of Phase I. A preliminary comparison of TAMVEC data with LRL data of 1961 showed close agreement. The internal consistency of the measurements was very good. Data corrections were only necessary for 3 runs out of a total of 3750. A report on the Texas A & M results is now in preparation.[9]

The success of the measuring program will ultimately be determined by the accuracy with which beam-producing fields can be calculated from the magnetic field data. In the Berkeley machine a satisfactory beam was produced on the first try with no adjustments to the calculated current configuration.

COST ANALYSIS

The approximate costs of the TAMVEC test program are given in Table II. These costs are significantly less than those of the 1961 LRL cyclotron measuring program. Direct comparison between the two programs is possible in the areas of data acquisition and data processing.[10] The Phase II data acquisition of TAMVEC required 20 man-weeks, compared with 154 man-weeks at Berkeley. TAMVEC data processing is approximately 90% complete 6 weeks after the measuring program was completed, whereas data processing at Berkeley was still in progress 8 months after the measurements were completed. Similar differences in costs exist in other phases of the program. These cost reductions are largely attributable to using the high-speed data-acquisition system and data-processing programs developed at LRL since 1961. The relatively high costs of mechanical design and fabrication were necessary to provide the required positioning accuracy. The extra effort in this area resulted in lower costs in data acquisition and data processing.

Table II. Distribution of expenses for TAMVEC test program.

Activity	Participating organization		Totals
	LRL[a]	TAMU	
Planning and coordination	3 800	4 400	8 200
Computer programming	1 400	4 000	5 400
General preparation - Mechanical design and fabrication	14 400	1 700	16 100
Capital equipment purchase	---	4 000	4 000
Shipping of test equipment and supplies	1 100	500	1 600
Setup in magnet and test program	3 700	5 700	9 400
Data Analysis	---	10 800	10 800
Totals	24 400	31 100	55 500

a. Expenses incurred by LRL and paid by Texas A & M.

CONCLUSIONS

The measuring program for TAMVEC has been successfully completed. The general form of the test plan is very suitable for sector-focused cyclotrons. The Rapid Mapper has been adapted to the measurement of large cylindrical magnets, and computer programs for data processing and analysis have been written. The system is readily adaptable to other cyclotron measuring projects and, in fact, will be used in August 1967 for testing the University of Maryland 102-inch cyclotron.

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