THE MAGNETIC FIELD SURVEY SYSTEM FOR THE TRIUMF CYCLOTRON MAGNET

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Abstract

The basis of the survey system is 105 equally-spaced flip coils mounted on a 27 ft aluminum I beam which rotates inside the 17.5 in. high vacuum tank. The I beam is moved through 1 deg increments (accurate to ±0.01 deg) by an air-driven indexing system capable of rotating both clockwise and counterclockwise. The coil signals are integrated and measured by a Reed scanning data acquisition system with a resolution of better than 1×10^{-5}. The overall absolute accuracy of the system is better than 1×10^{-4} at 5 kG. The acquisition of the data and the control of the I beam is handled by a 16 k core computer.

Introduction

The TRIUMF cyclotron magnet[1] is in the final erection stage at Vancouver and will be powered for the first time in November 1972. The measurement of the field and adjustment of each sector is a major part of the cyclotron commissioning program and is on the critical path. It must be completed satisfactorily before subsequent activities can continue. Once the field survey equipment is removed from the magnet gap and the resonators installed, a major effort would be necessary to dismantle and resurvey the field. These facts are important considerations in settling the survey design criteria.

Survey Requirements

The magnet has a cylindrical field volume approx 54 ft in diameter and 20.8 in. in height. The field strength on the median plane has a six-fold symmetry and varies with angular position and radius as shown by the contour model (Fig. 1). The beam in the cyclotron is confined to within ±1 in. from the median plane so that it is necessary only to determine the field profile on the median plane to be able to predict the beam orbit.

The H^- ions will travel about 20 miles as they are accelerated to the design energy of 500 MeV. The beam's turn-to-turn spacing is small, varying from 5.0 in. in the first turn to 0.06 in. at 500 MeV, and so to be able to predict the beam position with accuracy, it is necessary that the field be measured to an accuracy of ±0.5 G.[2]

The field has gradients up to 180 G/in. radially and 900 G/deg azimuthally.

The main magnet design has been based on measurements taken on 1/10 and 1/20 scale models. The main magnet survey will allow us to tailor the magnetic field, by using an adjustable pole profile, to fit the specifications required to achieve isochronous acceleration. The vertical component of the field must be tailored such that the following specifications are met:

1) The radial variation of the azimuthally-averaged field must fit the isochronous gradient requirement to better than 1 G/ft.

2) The flutter and spiral angle of the field must maintain ν_z within limits of 0.3 ± 0.1 and the relationship between ν_z and ν_r must be such that the beam spends as little time as possible in a region where $\nu_r - \nu_z = 1$. ν_z and ν_r are, respectively, the number of vertical oscillations and radial oscillations the beam undergoes per revolution.

3) The centring tolerances on the beam imply the imperfection harmonics be reduced to the order of 0.1 G. The measurement system will be able to detect 0.5 G harmonics. The rest will be adjusted with harmonic coils using the H^- beam as the field probe.

4) Because the H^- ion dissociates in high magnetic fields,[3] the maximum field allowed is 5.76 kG. This must be adhered to strictly.

Survey Technique

The field will be measured by a flip coil and integrator system. 105 coils will be positioned at 3 in. radial intervals starting at 12 in. and will be flipped 180 deg forward and backward to obtain the field values. The scanning beam (which rotates about the centre of the cyclotron) will be stopped for measurements at 1 deg intervals. At the periphery the points form an approximately rectangular grid of 3 in. × 6 in. At smaller radii the data density is much higher and some redundancy occurs. It is planned to use data points at 6 in. radial increments for radii in the range 111 to 207 in. and 3 in. radial increments elsewhere. If a coil integrator set fails during a measurement, the data for that point will be interpolated from adjacent points, and it has been shown that this interpolation provides the necessary accuracy. If measurements at two adjacent radial increments are lost, then the extrapolated data will not allow a sufficiently accurate determination of the important focusing parameter ν_z.[4]

Fig. 2 is a schematic control diagram showing the system and the location of components.

Survey Arm

The rotating beam is a standard 6 in. wide flange aluminum beam stiffened by two channels to reduce the horizontal vibration amplitude and which also serve as cable and air line ducts. The coils are mounted in nine units of 11 and one unit of 6 with each unit being rotated by its own driving mechanism.

Eleven coils are mounted on a 31 in. long type 304 stainless steel angle drilled at 3 in. centres to 0.003 in. on a milling machine. The stainless steel angle is mounted on two pillow blocks and is rotated by an air cylinder which drives through a rack and pinion mechanism. The stainless steel angle rotation is 180 deg ± 0.1 deg and this is controlled by adjustable stops. Each 11-coil assembly is mounted on an aluminum base dowel pinned to the adjacent plates. The dowel pin-holes, spaced by 33 in., are bored on a milling machine fitted with an optically-read quartz scale calibrated to 40 μin. The system accuracy allows us to state with confidence that radius of each coil is known to within ±0.010 in. Fig. 3 shows two coil assemblies mounted in the calibration magnet.

The main beam is 27 ft long and deflects naturally 0.30 in. under its own weight. The beam was prebowed upwards so that it will tend to sag to a horizontal position. The coil arrays will be individually levelled by shims to within 0.03 in. tolerance on height, and they will be aligned radially to better than 0.010 in.

The beam will pivot on a temporary centre post which has the greatest positional uncertainty of the whole system: ±1/32 in. This is unimportant because this position is repeatable, and the magnet will be adjusted about this centre which will become "the centre of the cyclotron". A pneumatic drive system is mounted at the outer end of the main beam, as shown in Fig. 4. The outer end of the beam rotates on a series of plates mounted inside the vacuum chamber with index bars mounted at 1 deg intervals. The index bars are mounted so that when clamped into position for measurement the beam is located azimuthally to within 0.01 deg. Any errors will be random as the index bars on each plate are dimensioned from a central reference and not from each other.

One air cylinder enables the main beam to be advanced or retarded by 1 deg increments and two auxiliary cylinders release and clamp the beam against the indexing bars to achieve the accurate positioning.

Field Probes

Although Hall plates had been used for all the model survey work, flip coils were chosen as the probe for the main survey for the following reasons:

1) Linear calibration curve.

2) Less stringent temperature control requirements (coil coefficient 4.5×10^{-5}/°C, Hall probe coefficient $\sim2\times10^{-4}$/°C).

3) Once a Hall plate is calibrated and aged it must be kept at a constant temperature, otherwise its sensitivity will change. The possibility of having to recalibrate 105 of these probes several times proved to be the deciding factor in favour of flip coils.*

The individual coils have approx 1000 turns of #30 AWG copper wire wound on an anodized aluminum bobbin. They are dimensioned to achieve the usual length-to-outer-diameter ratio of 0.72 which ensures that the field is measured at the coil axis and that the effect of field gradients is minimized. An attempt was made to obtain an exactly rectangular winding to achieve a constant turns density. This was found to be impractical and the coils were delivered as uniform as possible. All 105 coils were calibrated against a reference integrator and were found to have a sensitivity of 200.5 mV/kG with a standard deviation of 0.5 mV/kG.

Each flip coil is connected by plug and socket connectors to a twisted pair, shielded cable which feeds the induced signal to a patch panel and an integrator. Two types of cable were used. Between the coil and the socket on the main survey arm a short very flexible cable was required because of the thousands of flexes it will receive; Belden 8429 with an added flex insulation was found to be suitable. The cable between this socket and the patch panel is Belden 8451. The maximum length of cable from a coil to an integrator is 200 ft. All coils were calibrated with a 200 ft cable thus eliminating the need to correct for signal attenuation due to variable lead lengths.

Each numbered coil has been calibrated against a standard coil in a uniform field, and each integrator is calibrated against a standard integrator maintained under constant physical condition. Therefore, it is possible to use any coil with any integrator, and the survey procedure will be based on this available flexibility. Between 80 and 100 integrators will be used at any one time, depending on the demands of the survey.

The temperature coefficients of six sampled coils lie within the range from 4.5×10^{-5} to 5.0×10^{-5} per °C. During the survey the temperature of the arm carrying the coils will be monitored and any necessary corrections will be applied to the coil sensitivity.

Electronics and Data Acquisition

The integrator circuit (Fig. 5) is based on a chopper-stabilized operational amplifier with a teflon capacitor and metal film resistors in the feedback loop and the potential loop. The temperature coefficients of the elements were carefully chosen so that the overall system would have a small coefficient. The measured coefficients vary within a range expressible as $3.0 \pm 2.5\times10^{-5}$/°C.

*Flip coils supplied to our specification by Electronics Craftsmen, Waterloo, Ont., Canada.

The output is adjusted to give an overall sensitivity of 200 mV/kG of field parallel to the axis of the resting flip coil. The maximum signal during the survey is therefore less than 1.2 V, and this is measured to six digits by a Hewlett Packard 2402A digital voltmeter (DVM). This DVM is connected in turn to the integrators by a Hewlett Packard 40-channel Reed scanner, type 2912A and its 100-channel extender, type 2920A. The DVM can read the integrators at a maximum speed of 25 channels per second.

The racks containing the integrators are located in the control trailer and maintained at ±5°F. The humidity in the measuring area is known to be constant within the range from 50 to 65%.

Errors in the DVM and scanning system have been studied to some extent but basically one relies on the manufacturer's specifications. The long-term absolute accuracy of the DVM plus scanner is claimed to be better than 0.12% ± 0.05% full scale, yielding a maximum field error (over six months) of about 0.85 G at 5 kG and 0.75 G at 1 kG.

Observation of random errors on one coil-integrator circuit shows that, on the forward "flip" and on the reverse "flop", a 1.0 V signal is reproduced within ±0.03 mV. The average signal is therefore subject to maximum errors of the order of ±0.02 mV, corresponding to a random field error of ±0.1 G.

A study has been made of the DVM readings obtained from 11 coils when the scanner system is working at full speed. This indicates that the field estimates are predictable and reproducible to within 0.5 G over the range from zero to 6 kG, over a period of several weeks with no adjustments made to the correction potentiometers in the integrator circuit.

The calibration procedure used to standardize flip coils and integrators is carried out with a uniform-field calibration magnet and an Alpha NMR unit as reference.

One source of error requiring continued attention is the magnetic behaviour of stainless steel used in various parts of the survey system. Although this metal is paramagnetic, samples subjected to stress or incomplete heat treatment can show marked ferromagnetic behaviour. This effect has been noted in the stainless-steel bolts used to mount the flip coils on the channels. The coils showed non-linear output in varying magnetic fields, and the effect was removed by annealing the bolts, as shown in Fig. 6.

There remains a small residual non-linearity in coils located at the ends of a channel, due to the welded box sections: in precise work a small correction may be applied to data from such coils.

Control System and Diagnostics

The control for the system is provided by the Hewlett Packard 2116B computer. It carries out the following functions:

1) Provides a sequence of commands to the survey channel to flip and flop the coils and then to move the channel to the next angular position. These commands are routed to the air solenoids via an operations control box and can be run manually or remotely. The angular indexing is done after the computer has

2) acquired the necessary data from the Reed scanner, DVM data acquisition system, and

3) made routine analysis checks on the data to ensure that the flip coils and integrator are working properly. Some of these checks are:

   - the flip and flop values are compared
   - the measurements from adjacent coils are compared.

   If these comparisons fail any criterion, then a diagnostic message is printed on a teleprinter. The operation then has three options:

   a) accepting the data and continuing
   b) repeat measurement at that position
   c) aborting the run

4) Once the data has passed these preliminary tests it is stored on 9-track magnetic tape for subsequent analysis at the UBC Computing Centre.

Central Region Cyclotron Magnet Results

A prototype of this survey system (using six flip coils) with essentially the same electronic elements but a different flip mechanism was used in surveying the magnet for the cyclotron used in studying axial injection problems for TRIUMF.[5] The coil measurements were directly compared with Hall probe measurements. The two techniques were in agreement to ±1 G. The Hall plates had to be recalibrated several times during the survey, with typical sensitivity changes of 0.1%. The flip coils were calibrated twice, at the beginning and the end of the survey. The results of these two calibrations are shown below:

Coil No.	1 Nov 18/71	2 Dec 23/71	Difference
1	218.15	218.12	0.015%
2	217.60	217.50	0.05
3	218.91	218.83	0.04
4	217.40	217.46	0.03
5	218.28	218.20	0.04
6	216.20	216.05	0.07

Means of Adjusting Magnet

The TRIUMF magnet has three mechanisms for adjusting the median plane field to achieve isochronism, correct focusing, and uniformity for all six sectors. These are:

a) main excitation
b) pole shims
c) trim and harmonic coils

Main Excitation

The main coil current has been predicted from model measurements on 1:20.8 and 1:10 models which included simulated supporting structures. The magnet is assembled in a concrete vault, and the floor and wall support beams and reinforcing rods will affect the main field to a small but significant extent so that the main coil excitation may be modified from that predicted by the models.

Pole Shims

The poles are built undersized and are shimmed to a predicted profile by means of removable plates bolted to the pole sides. A study and calibration of shim effects[6] has led to a shim prediction program which computes the pole shim profile required to vary the magnet average field and focusing parameters by small amounts. The results of a field survey will therefore be analysed to compute the required shim changes. There are 70 shim positions on each pole, and the upper and lower poles must be made identical, so that a careful bookkeeping system will be necessary to record and keep track of the shims. The aim of the survey is to achieve an average field correct to within 1 G of isochronism at all radii by adjusting the pole shims.

Trim and Harmonic Coils

Finally, electrical shimming will be achieved by exciting 55 trim coil-pairs to achieve variations in the radial field gradient of zero to 2 2 G/ft or by exciting harmonic coils to achieve local perturbations of 7.5 G. There are 13 sets of harmonic coils with radial increments of 26 in. per sector.

The perturbation of the main field by each pair of coils must be measured to enable corrective current settings to be computed when some or all are excited simultaneously. The final coil excitation settings will be determined by monitoring the accelerated beam position.

Operation and Schedule

The full 360 deg field survey will require approximately three hours. The system timing is as follows:

Release clamps and move main beam ahead by 1 deg and reclamp	7 sec
Allow beam settling time	5 sec
Flip coils 180 deg forward	1 sec
Settling time	5 sec
Read integrators and reset to zero	4 sec
Flip coils 180 deg backward	1 sec
Settling time	5 sec
Read integrators and reset to zero	4 sec
	32 sec

It is assumed that the main field will be surveyed in one-half of a shift and that the data will be sent for analysis on the main UBC computing system. A review of the analysis and plans for trimming the magnet will take a further full shift. Adjustments to the magnet may also require one full shift, so that the main survey will not be repeated for at least three shifts. During the lulls in the main survey it will be possible to do calibration surveys of the trim and harmonic coils and some of the auxiliary surveys in the injection and extraction regions and the median plane survey.

The time allotted for the main survey is 100 working days or 4.5 calendar months. During this time it is estimated that the whole field area will be surveyed approximately 35 times.

Acknowledgements

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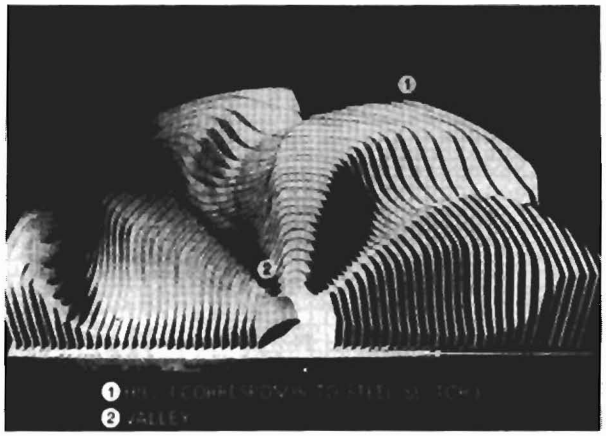

Fig. 1. Model of field profile showing radial and azimuthal variations

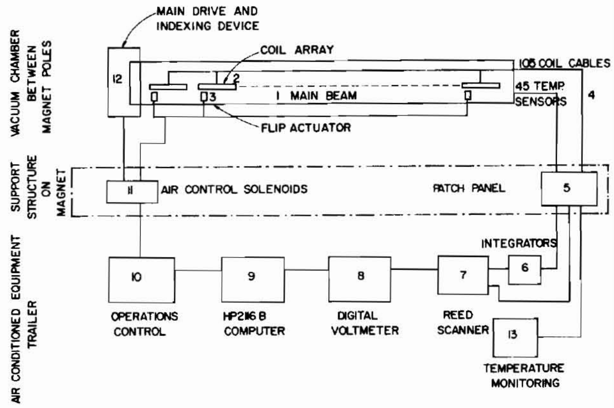

Fig. 2. Field survey equipment components and their location

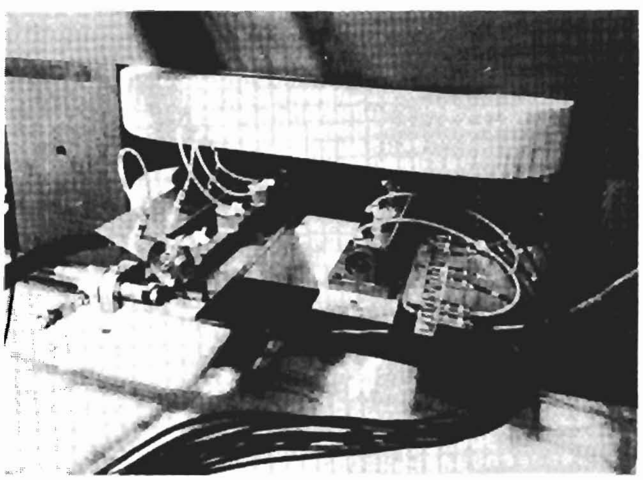

Fig. 3. Flip coil assemblies in the calibration magnet

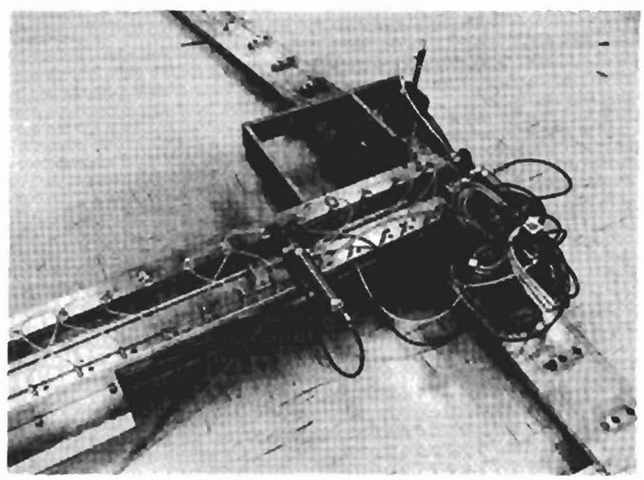

Fig. 4. Main beam outer end showing the drive mechanism and flip coil assemblies

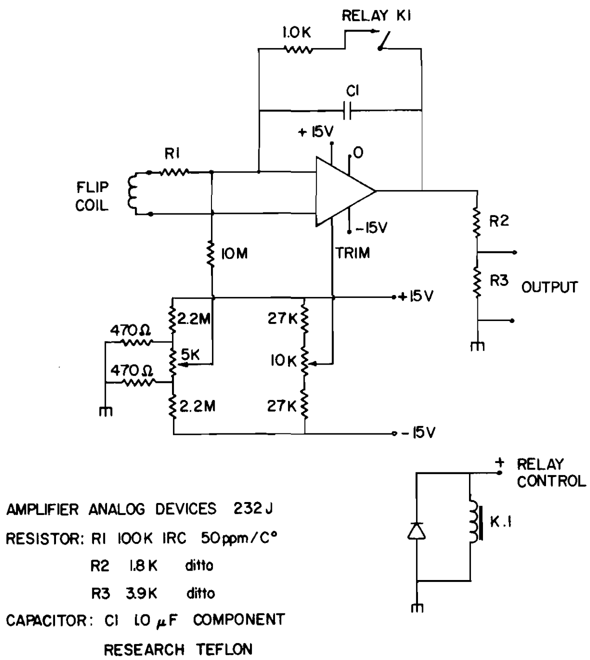

Fig. 5. Integrator circuit

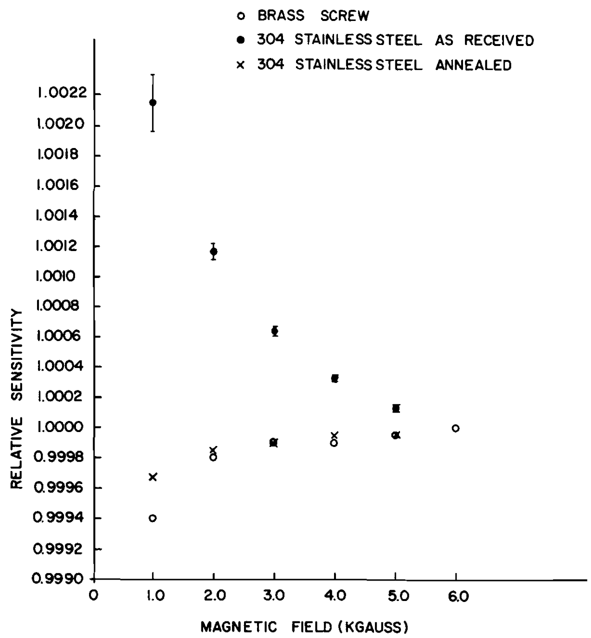

Fig. 6. Effect of mounting screw material on the flip coil sensitivity