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MAGNETIC FIELD CONTROL IN A BETA-RAY
SPECTROMETER

M.S. Thesis Submitted to Iowa State University, November, 1972

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Magnetic field control in a beta-ray spectrometer

by

James Kent Halbig

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I. INTRODUCTION

In the field of nuclear spectroscopy the magnetic beta-ray spectrometer has proven to be a valuable research tool. There are many designs for magnetic beta-ray spectrometers, all of which utilize the principle that the paths of charged particles are bent in a magnetic field. The beta-ray spectrometer used in this work has been described in detail by Eitter and Talbert (1).

The essential operation of the spectrometer can be described briefly with the aid of figure 1. A radioactive source which emits beta particles (electrons) is located at the source position S. Immediately in front of the source is a slot which defines the electron beam. A detector is located at position D. The source, source slits and the detector are all located on the same characteristic radius ρ . An electron moving transversely in a uniform magnetic field follows a circular path of radius, r which is given by

$$r = P/(qB)$$

where P is the electron's momentum, and q is its charge. The strength of the magnetic field is represented by B . Hence, for a particular field strength only electrons of a specific momentum will be seen by the detector. In the $\pi/2$ magnetic spectrometer, the magnetic field has rotational symmetry and the magnetic field varies along the radius

Figure 1. The beta-ray spectrometer

approximately as

$$B \propto \left(\frac{1}{r}\right)^{\frac{1}{2}}$$

where here r is the radial distance from the axis of symmetry. These characteristics spatially focus the electron beam (2). In principle, then, one can use this instrument to investigate particles of a particular momentum by proper choice of the magnetic field strength. In reality, however, there are aberrations inherent in the design of the spectrometer which, by adjustment of the field shape, can be minimized but not eliminated, and source width effects and source thickness effects which cause a "defocusing" of the electrons. Thus in figure 1, electrons with paths 1 and 3 see different average fields than the electrons with path 2 which are seen by the detector. As the defocusing effects of the electron beam decrease, the resolving power of the spectrometer increases.

The high-resolution, magnetic beta-ray spectrometer is unequaled in its potential ability to resolve structure in a low-energy beta spectrum, and to measure higher energy (3-8 MeV) electron spectra with low distortion.

To fully realize this potential it is necessary to be able to set, maintain and reproduce the magnetic field in the beta spectrometer. Noise and short term drifts in the system which supplies the current to the coils of the spectrometer can reduce the resolving power of the spectrometer. In addition, any drift in the system can degrade both the accuracy

of calibration and the reproducibility of the instrument.

Since the advent of studies of short-lived nuclei with half-lives of the order of seconds it has become necessary to require that the field control system also have a rapid settling time, i.e., the time necessary for the magnetic field to stabilize to within limits set about the desired magnetic field value. Otherwise significant amounts of source activity can be lost while the field is stabilizing to within the field limits at which data is to be taken. Furthermore, the duty factor, i.e., the percent of the total run time that activity is being collected and/or data are being accumulated, is appreciably reduced.

For iron-free spectrometers, it is sufficient to have a good quality, programmable constant-current supply. It is necessary then only to provide the proper programming voltage to obtain the desired field, since the field is directly proportional to the current which is directly proportional to the programming voltage. For spectrometers with iron pole faces, the situation is not so simple. The hysteresis of the iron does not allow a unique field value to result for a given current supplied to the magnet coils, and the field is not a linear function of current since the relative permeability of the iron is a function of the magnetic field.

For iron spectrometers, a peaking-strip technique has been used as a reliable method to control the magnetic field.

(1,3,4). This technique requires that an iron-free solenoid be placed inside the magnetic spectrometer with the field of the solenoid aligned antiparallel to the field of the spectrometer. Current is supplied to the solenoid by a programmable, constant current source. The field inside the solenoid is directly proportional to the current from the current source and hence, to the programming voltage. After the field has been set in the solenoid, the current in the spectrometer magnet is changed until its field exactly cancels the field due to the solenoid at the center of the solenoid. The current in the spectrometer is changed by a voltage proportional to any non-null field at the center of the solenoid. This voltage is fed back to the controlling electronics.

Field control using a direct field measuring device in place of the solenoid is possible; however, direct measurement of magnetic field strengths from 10 to 1000 gauss on a single range to within several milligauss is difficult. With rotating-coil magnetometers, such accuracy and stability is on the edge of practicability¹ and the mechanical nature of the probe requires frequent servicing and is a continual source of headaches. Hall-effect devices are plagued with

¹Lush, M. J., President, Rawson-Lush Instrument Co, Inc., Acton, Massachusetts. Private Communication. 1972.

two problems¹. The first is that the temperature dependence of the Hall probe is nominally 50 parts per million per centigrade degree, and that the temperature dependence of the associated electronics is nominally 100 parts per million per centigrade degree. The second is a signal-to-noise ratio problem when trying to resolve 2.5 milligauss on the 1 kilogauss scale. It becomes apparent then that the solenoid coil, combined with a null probe, is the most satisfactory means of controlling the field in a high-resolution beta-ray spectrometer.

The original design of the field control system used for the TRISTAN beta-ray spectrometer utilized the peaking-strip technique. A block diagram of this design, which is presented by Eitter and Talbert in the detailed description of the beta-ray spectrometer (1), is shown in figure 2. The Programmable Digital Field Selector (PDFS) and the Alpha Scientific power supply have replaced older equipment described by Eitter. For completeness it is necessary to add only that the PDFS in conjunction with the Fluke Voltage Supply 383B/A provides the voltage which programs the Alpha Scientific power supply. The programming voltage changes from one value to another through a series of 40 microvolt steps, each step

¹Chapman, Dick, Chief Engineer, F. W. Bell, Inc., Columbus, Ohio. Private Communication. 1972.

Figure 2. Block diagram of original magnetic field control system

is equivalent to 2.3 milligauss. The stepping rate is nominally 500 steps per second for an increase in field and 1500 steps per second for a decrease in field.

The original specifications set down for this system required field reproducibility and stability of 10 milligauss. Because of the ambiguity of the manner in which the tests of system performance were carried out by Eitter and Talbert, the performance of the system was re-evaluated, this time using the PDFS and the Alpha Scientific power supply. The results revealed three highly undesirable characteristics:

- 1) Drifts exceeding 95 milligauss were observed.
- 2) The stabilization time, i.e., the time after completion of current stepping required for the field to restabilize within 10 milligauss of the desired field, was found to be 4.8 seconds for a 0.115-gauss step, 8.0 seconds for a 0.23-gauss step and 12.4 seconds for a 2.3-gauss step.
- 3) For field steps larger than 18 gauss the field error became so large that the error signal from the magnetometer probe changed polarity, resulting in system instability.

The third characteristic is extremely harmful when the field control program recycles the field from its maximum value to

its minimum value, a step normally much greater than 18 gauss.

The design problem of this work was to develop a magnetic field control system for the TRISTAN beta-ray spectrometer which would meet the following requirements for fields from 10 to 1000 gauss.

- 1) Field stability and reproducibility to within 10 milligauss.
- 2) Control system stability for any size field step.
- 3) Settling time of less than 2 seconds for a 0.23-gauss field step.

II. ANALYSIS

The response functions of the various components used in the control system were experimentally determined. The procedure followed for the power supply-coil subsystems was to use a Sanborn Model 297 chart recorder to monitor the response of the subsystems to a step input. A diagram of this setup is shown in figure 3. These data were then fit by an assumed function using a program (5) which adjusted the parameters of the assumed function to obtain a minimum least-squares fit. The response function of the Hewlett-Packard magnetometer and its probe was determined from an experimentally determined frequency response.

A. Spectromagnetic Supply - Spectrometer Subsystem

Basically, the spectrometer consists of ten coils in series. Each coil is shunted with a variable resistor which allows adjustment of the relative currents through the individual coils and hence, of the field shape inside the spectrometer. A simplified model was used in the analysis of the spectrometer. This model, shown in figure 4, uses one coil and one shunt resistor in place of the ten LR parallel circuits in series. The resistance of the spectrometer coils, R_L , is 31.5 ohms. The shunt resistance, R_S , is 288 ohms. The capacitance C is internal to the power supply and

Figure 3. Setup used to determine response of power supply - coil subsystems

Figure 4. Simplified model of the spectrometer used in the analysis of the response of the Spectromagnetic Supply - Spectrometer subsystem

has a value of 120 microfarads. The value of the inductance of the spectrometer coils, L , is approximately 19 henrys. As a first approximation then, one may assume that the response of this subsystem will be dominated by the response of the spectrometer coils. Analysis of the system in figure 4 reveals that

$$I(s) = I_o(s) \frac{\omega_n^2 (1 + as)}{s^2 + 2\delta\omega_n s + \omega_n^2}$$

where

$$a = \frac{L}{R_L + R_S} \quad 2\delta\omega_n = \frac{R_L}{L} + \frac{1}{R_S C}$$

and

$$\omega_n^2 = \frac{R_L + R_S}{LCR_S}$$

The discrete points in figure 5 represent data indicating the response of this subsystem to a step input. The error bars represent the uncertainty in reading the data from the strip chart recorder. These points were fit using the equation

$$R(T) = N \left[1 + \frac{D}{A} \exp(-X_1 \omega_n T) \sin(\omega_n A T + \Phi) \right]$$

where

$$A = \sqrt{1 - X_1^2}$$

$$\omega_n = \frac{\pi}{A} \frac{1}{X_3}$$

$$D = 1 - 2(X_1 X_4 \omega_n) + X_4^2 \omega_n^2$$

$$\Phi = \text{ARCTAN} \left[\frac{X_4 \omega_n A}{1 - X_1 X_4 \omega_n} \right] + \text{ARCOS} (X_1)]$$

$$T = T' + X_2$$

which is the inverse transform of the transfer function of the Spectromagnetic Supply - Spectrometer subsystem where T' is the elapsed time measured from the time the step input function was applied. The parameter X_2 was introduced to allow for error in designating the time at which $T' = 0$ on the strip chart. A small error in T' greatly affects the character of the fit function, and hence, prohibits the true determination of the other parameters which are linked to the control system response. The time at which the output reaches its first relative maximum value is the physical interpretation of X_3 . The coefficient N is a normalization coefficient. The parameter X_1 corresponds to δ in the transfer function, and X_4 corresponds to a . The parameters which gave the fit represented by the solid line in figure 5 give

$$a = 0.282$$

$$\delta = 0.766$$

$$\omega_n = 4.548$$

The value of X_2 was 0.0115, which is much less than the uncertainty in determining $T' = 0$ from the strip chart.

Figure 5. Response of Spectromagnetic Supply - Spectrometer subsystem to a step input

The quality of the fit shown in figure 5 allows one to conclude that the model shown in figure 3 accurately describes the subsystem and that the parameters of the transfer function of this subsystem are those given above.

B. Alpha Scientific Supply - Solenoid Subsystem

The experimental response of the Alpha Scientific Supply - Solenoid subsystem represented by discrete points in figure 6 was fit using the inverse Laplace transform of the transfer function,

$$TF = M/(S + E).$$

The solid line shows the fit achieved using $E = 9.4582$; M is a normalization constant.

C. Magnetometer - Probe Subsystem

The frequency response of this subsystem was determined by wrapping a coil of wire around the magnetometer probe and applying a signal of known frequency and amplitude to the coil while at the same time monitoring the output of the magnetometer. A block diagram of this setup is shown in figure 7.

The experimental response for this subsystem is shown by the discrete points in figure 8. The fit to these points is that of a system with a single pole on the real axis at -605 radians per second. This is obviously not a good fit beyond

Figure 6. Response of Alpha Scientific Supply - Solenoid subsystem

Figure 7. Setup used to determine response of Magnetometer - Probe subsystem

Figure 8. Frequency response of Magnetometer - Probe subsystem

4000 radians per second; however, since the other system components have much narrower frequency responses, such a model is adequate here to describe the Magnetometer - Probe subsystem; therefore, the transfer function can be specified as

$$TF = J/(S + H)$$

where J is a normalization constant and $H = 605$.

D. Non-constant Permeability Effects

The voltage necessary to offset the non-constant permeability effects in the spectrometer as a function of current in the spectrometer coils is shown in figure 9. These data represent the integrated error voltage which must be supplied, in addition to the programming voltage for a given current in the solenoid, to the input of the Spectromagnetic power supply to attain a null field at the center of the solenoid. The voltages were measured with a Cimron P9500B digital voltmeter.

Before these data were taken, the spectrometer was completely demagnetized by driving the spectrometer field around successively smaller hysteresis loops until the residual magnetism of the iron in the spectrometer was reduced to near zero. The demagnetization was required to eliminate hysteresis effects.

To complete the discussion of the analysis it should be pointed out that the two subsystems A and B above are only

Figure 9. Non-constant permeability effects on error voltage necessary to null field at the center of the solenoid

piece-wise linear inasmuch as they are electronically controlled only when the output voltage change required to maintain or achieve the programmed current change is less than a given amount. If the required voltage change exceeds this given amount, the powerstats are mechanically turned up or down and the systems can no longer be treated as linear systems with the transfer functions given above. Figure 10 shows the response of the Spectromagnetic Supply - Spectrometer subsystem to a step input which was sufficiently large to cause the powerstat to slew. At point A on the curve the step input was removed. The effect of the limited linear ranges of the supplies was found to manifest itself about every 6 gauss in the region from 25 gauss to 125 gauss. The problem will not be encountered frequently in measurements of internal conversion electron peaks which typically require steps of 0.025 gauss over a region of 1 gauss. For measurements of continuous beta-ray spectra, however, the problem will be encountered more often. Although there are instances where these subsystems become non-linear, it is beyond the scope of this work to do a non-linear analysis of the total system, and it is sufficient to assure that the non-linearity will never cause a condition where the field will not stabilize.

Figure 10. Non-linear response of Spectromagnetic Supply - Spectrometer subsystem

III. DESIGN

A. Intuitive Discussion

Two different designs were proposed. Both were born of intuition. In the original design of the field stabilizer, a zero steady-state error was assured and stability could be assured by proper choice of the integration parameter. The stabilization time was then limited by the integration parameters necessary for stability and by the voltage which the integrator must provide to obtain zero steady-state error.

The first design, referred to as system 1, considered that a better response could be obtained by making as small as possible the integrated voltage necessary to achieve zero steady-state error. Since it is essentially only the non-constant permeability of the iron in the spectrometer magnet which prevents the field of the spectrometer magnet from being exactly proportional to the field in the solenoid, a good first try at the new design appeared to be to externally program the Spectromagnetic power supply with a voltage proportional to that which programs the Alpha Scientific power supply. Then the integrator need only supply the voltage necessary to offset the error due to the non-linear permeability effects. This voltage is small compared to that required to program the Spectromagnetic supply.

The signal flow diagram for system 1 is shown in figure 11, where K is the proportionality constant which, except for non-linear permeability effects, matches the fields of the solenoid and spectrometer magnet. The transfer function for the field of the Alpha Scientific Supply - Solenoid subsystem is F_{2S} and F_{1S} is the transfer function for the current in the Spectromagnetic Supply - Spectrometer subsystem. The proportionality constant which converts the current in the spectrometer coils to magnetic field is FC_1 . The transfer function H_Y represents the non-constant permeability effects. The transfer function of the magnetometer null detector is F_{06} , and A/S is the transfer function for the integrator.

The second design, system 2, incorporated the idea that a feedback loop in parallel with the integrator of system 1 should further improve the response of the system. Care had to be taken to maintain stability and to choose the proper gain in the feedback loop so that the response is indeed improved. The signal flow diagram for this system is shown in figure 12. The transfer functions are as previously defined with the exception of K_F which is the gain of the parallel feedback.

B. General Response Analysis

While intuition is sometimes a good starting point for design, a more rigorous foundation is desirable. To provide

Figure 11. Signal flow diagram of system 1

Figure 12. Signal flow diagram of system 2

this more rigorous foundation, a Linear Systems Analysis Program (LSAP) was used¹. LSAP is an integrated package of procedures that performs numerical computations which are frequently needed in the analysis and design of both continuous-time and discrete-time control systems. The program contains procedures which, among other tasks, will form a transfer function, find its associated frequency response, determine its response to an input which can be represented by a simple Laplace transform, and provide data for a root-locus plot.

One final simplification was made in the analysis. The analytical function which fits the non-linearity permeability effects curve was not determined because of the obvious complexity of the analysis involved and because the change in the error voltage over the range of steps taken during actual operation is very small. Instead, values representative of the total range of operation were used to investigate the effect of the magnitude of the error voltage on the poles of the system. The position of the poles was virtually unchanged as HY varied between its maximum and minimum values. Again, the prime consideration is that the desired settling time is achieved and that stability is never lost.

The root-locus diagram for system 2 is shown in

¹Duven, D. J., Electrical Engineering Department, Iowa State University. Ames, Iowa. Private Communication. 1972.

figure 13. Roots further out on the negative real axis have been suppressed because they have very little effect on the system performance and for simplicity in presentation. The root-locus diagrams in figure 14 show the effect of adding the parallel feedback, K_F , in system 2. The open circles on the two plots are loci for similar value of A , i.e., the right most open circles on both plots correspond to the same values of A . Again poles have been suppressed for clarity. It is readily apparent that the addition of K_F increases the stability of the system for a given value of A . Furthermore, the settling time to within 10% of the final value of a step is shortened. For the value of $A = 2.0$ the settling times to 10% are 18.0 seconds and 0.4 seconds for system 1 and 2 respectively. These results support the intuitive ideas.

Once the stability of the systems was confirmed, a prototype of the stabilizer was constructed, and the actual values of the parameters A and K_F were determined experimentally. Calculation of these parameters was not attempted because of the approximations which have been made and because the staircase input for a finite time is difficult to treat analytically.

The analysis leading to the root-locus diagrams gained credibility when a value of A approximately equal to four was used in the stabilizer prototype with K_F equal to zero. The root-locus diagram labelled $K_F = 0.00$ in figure 14 shows the

Figure 13. Root-locus diagram of system 2.
Parameter varied is $A = 1/RC$.

Figure 14. Root-locus diagrams of systems 1 and 2.
Parameter varied is $A = 1/RC$.

system to be marginally stable for the value of A approximately equal to two. Considering that approximations have been made in arriving at the transfer function of the system, this agreement is quite good.

C. Stability

Once the parameters of the system have been determined, one must be mindful of the criteria dealing with field reproducibility and stability. To insure stability and reproducibility of the field settings, low-offset and low drift amplifiers and a well regulated power supply, Zeltex ZM15200, were used. All amplifiers used had noise specifications which were below 5 microvolts. Input and shunt resistances were chosen such that noise and offset currents through them would not produce voltages greater than 50 microvolts. A voltage of 50 microvolts at the input to the Spectromagnetic supply is equivalent to a current change of 10 parts per million of the maximum current. Equal valued, precision resistors were used in the voltage dividers (Appendix) to insure that heating effects would be held to a minimum.

IV. EVALUATION

A. System 1

System 1 with the experimentally determined optimum design parameter $A = 11$ met the first two design criteria but fell short of the third. The field stability and reproducibility were checked by repeatedly collecting data over the strong conversion line found in the beta decay of ^{137}Cs . The rms deviation of the field which focuses the leading edge of this conversion line is a measure of the stability and reproducibility of this system, and has been found to be 3.1 milligauss. The maximum deviation from the mean value, observed over a 48-hour period, was 20.2 milligauss.

The system was found to be stable for any size field step. The system was run from zero field to its maximum value of field and returned to zero. System stability was maintained in both cases.

This system design failed to meet the stabilization time specification. The stabilization times for the original system, system 0, and systems 1 and 2 are listed in table 1. The stabilization times for a 0.23-gauss step at 34.5 gauss and a 11.5-gauss step at 23 gauss were chosen as being representative of the stabilization times for the respective step sizes over the entire range. The stabilization times were measured by starting the digital programmer to increase the

field by the desired number of steps and at the same time starting a timer. The timer was stopped as soon as the non-null field in the solenoid, as indicated on the Hewlett Packard magnetometer, dropped and remained below 10 milligauss. The time necessary for the field to be increased by the desired number of steps was subtracted to give the stabilization times. Several readings were taken for each case and the times were reproducible to within 0.1 second.

B. System 2

System 2 with the experimentally determined optimum design parameters $A = 16.2$ and $K_F = 0.0016$ met all of the design criteria. The measurement procedures were the same as those described for system 1. The settling time for a 0.023-gauss step was less than 0.5 second. For steps larger than approximately 0.085 gauss the stabilization time was

Table 1. Comparison of stabilization times

System Identification	Stabilization Times (Seconds)	
	0.23-gauss step	11.5-gauss step
0	7.8	49.2
1	4.6	6.0
2	1.8	1.8

constant and equal to 1.8 seconds. The field error for these larger steps does not exceed the value of 20 milligauss during the step. This guarantees that a 180° change in the phase of the magnetometer output (mentioned in the introduction) will not occur.

As was mentioned previously, one must assure that the control system will remain stable when the non-linear slewing of the Alpha Scientific and Spectromagnetic supplies occurs. This assurance was provided by the absence of instabilities during testing which included the worst case condition, specifically, to increase the field from zero to its maximum value, to allow the field to stabilize at the maximum value, and then to decrease the field to zero.

C. Unpredicted Instability

An observation was made which is apparently a contradiction to the root-locus diagrams. It was observed that as K_F was increased system 2 became unstable. The root-locus diagrams in figure 14 indicate that as K_F is increased, the stability of the system is increased. This paradox may be resolved by attributing the unexpected behavior to a transportation lag in the Spectromagnetic power supply. Such a transportation lag would introduce a multiplicative term, e^{-TS} , where T is the transportation lag in the Spectromagnetic Supply - Spectrometer transfer function.

Analysis of such a system could be done by expanding e^{-TS} as a series; however, an acceptable design has been found without this extensive analysis, and it is sufficient to state that a transportation lag has been observed in the Spectromagnetic power supply and that such transportation lags have been known to cause instabilities in similar systems when the parallel feedback becomes too great¹.

¹Skank, Harold, Instrumentation Group, Ames Laboratory, USAEC, Ames, Iowa. Private Communication. 1972.

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VII. APPENDIX: CIRCUIT DIAGRAM

A simplified schematic of the control circuitry is shown in figure A1. The error voltage input comes from the Hewlett-Packard magnetometer. The programming voltage input is supplied from the Fluke voltage calibrator which has a maximum output of 50 volts. The Alpha Scientific power supply requires 20 volts input for maximum current. One tap of the voltage divider provides the correct proportion of the programming voltage to the Alpha Scientific supply. The other tap supplies twice the proper proportion of the programming voltage to the summing amplifier B, e.g., 10 volts for a Fluke output voltage of 50 volts. The additional factor of two attenuation is provided by the summing amplifier B.

The error voltage is integrated with a time constant $\tau = RC$ where C is fixed at 90 microfarads. The design parameter A referred to in the text of the thesis is related to the circuit component values by the equation

$$A = \frac{0.5}{RC}$$

The factor 0.5 comes from the attenuation of the signals applied to the non-inverting inputs of amplifier B. The error voltage is also reduced by the ratio

Figure A1. Schematic diagram of field stabilizer

$$KF = \frac{R_{d2}}{R_{d1} + R_{d2}}$$

and summed by amplifier B. The ratio KF is the design parameter associated with the parallel feedback. The output of amplifier B provides the input to the Spectromagnetic power supply. It should be noted that in the actual control circuit A and KF are effectively a factor of ten larger due to the magnetometer gain used during normal operation.

Amplifier D serves as a high-impedance buffer for the integrator. This allows the control circuit to be used in an operate-hold type system in which the error voltage is removed from the input to the integrator and the integrated error voltage remains constant, when the system is switched from the operate mode to the hold mode.