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AUTOMATIC MAGNETIC MEASUREMENT FACILITY FOR SYNCHROTRON MAGNETS*

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Paper to be presented at the Third International Conference on Magnet Technology, Hamburg, Germany, May 19 - 22, 1970

ABSTRACT

A computer-controlled facility has been developed and used for studying model bending magnets and quadrupoles for the 200 GeV synchrotron. With the use of fast sample-and-hold circuits, measurements are taken under pulsed conditions simulating actual synchrotron operation. The computer performs immediate analysis of the data, such as quadrupole harmonic analysis or calculating the bending magnet sextupole component. Accurate probe position is attained with a standard lathe bed. Translation is controlled automatically by a closed-loop system consisting of variable-speed motors, Moire-fringe linear position transducers, and the computer. Carriage wobble is compensated by an auto-reflecting laser controlling probe-tilting motors. In this work, integrators with extremely low drift have also been developed.

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I. INTRODUCTION

The system described here is based on a small general-purpose digital computer, a selected set of useful peripherals, general-purpose interface equipment, and a large, accurate probe positioner, plus two additional probe positioners. Based as it is on general-purpose equipment, it provides great flexibility in the measurements taken and in the methods of making them. The use of FORTRAN for all but the lowest-order controller routines makes programming for a new application relatively simple. Furthermore, for almost all kinds of measurements the data reduction is completed on the same computer in a second phase of operation. In some cases data from our system has also been read in and analyzed by a large batch processing computer. Writing the data on magnetic tape from our machine in the BCD mode makes it possible to read it into the large computer with no special conversion routines.

An additional feature of the computer system is that it is mounted so that it is portable and can be rolled or carried in a relatively short time to any place where it needs to be used.

In planning our magnetic field measuring system we have followed some of the ideas used at Lawrence Radiation Laboratory[1] and Argonne National Laboratory.[2] Figure 1 is a block diagram of the system.

II. DETAILS OF THE HARDWARE

The following is the configuration of the computer and peripheral equipment:

Computer: Varian 620/i 8,192 words, 16 bits

Teletype, ASR-35

Calcomp plotter Model 565

PEC magnetic tape transport, 7 track, 556 bpi, 25 ips

The A/D system consists of a Redcor Model 611933 Analog-to-Digital chassis and a multiplexor accepting input from 10 fast sample-and-hold circuits and 6 direct inputs. The entire electronics package has successfully operated in an environment with a wide range of temperature, humidity, and dust conditions in an inhospitable building. A Sola line filter has proven adequate to eliminate any noise problems from the SCR power supplies used for magnet testing. Two-hundred-foot-reels of tape have proved most useful for storage of programs and data.

We have checked the two-way compatability between the PEC tape unit and the IBM 360/75 and the CDC 3600.

The principal probe-positioning device is a standard 7-foot lathe bed with horizontal and vertical cross slides having 12-inch travel each. Figure 2 is a photograph of this device. Motion in all three directions is provided by variable-speed motors controlled by the computer. Horizontal and vertical transverse position is measured by Moire-fringe linear position transducers with a least count of 0.0001 inch. A subroutine closes the loop between the position measurement and the motor control and sets any desired position with an accuracy of better than ± .0005 inch. Automatic positioning in the long axis has not yet proved necessary.

The second probe-positioning device is also a standard lathe bed. The longitudinal motion and the horizontal transverse motion are controlled by digital stepping motors. The angular resolution of each motor is 200 steps per revolution, which provides a minimum longitudinal motion of 0.00125 inch and a minimum transverse motion of 0.0005 inch.

The third probe-positioner is used for coils which measure the harmonic content of quadrupoles. A digital stepping motor positions the coil to measure field as a function of angle. The least count is 31 milliradians.

III. INTEGRATORS

The high quality of the magnets being studied, together with the slow pulsing rate, made it necessary to develop integrators with high sensitivity and extremely low drift. For example, in the bending magnets we needed to measure gradients as small as 0.01 G/cm, either using DC operation or under pulsed operation with the magnet taking about 1.6 seconds to achieve full field. With a pair of search coils separated by one centimeter, and having turn-areas of about 10^3 cm^2, one had to deal with signals as small as 0.1 μV-sec. We developed integrators embodying as many techniques as possible for reducing the drift one finds with a closed-circuit input. The circuit diagram of our final design[3] is shown in Figure 3. The operational amplifier is an Analog Model 230J solid state amplifier,[4] chosen for its good offset characteristics. (This amplifier gave us the best overall drift performance of many amplifiers that we tested.) The amplifier uses a solid state chopper. The integrating capacitor is a 1 μF polystyrene type chosen for small dielectric absorption, small temperature coefficient, high stability, and high insulation resistance - about 10^6 megohm. Additional features of the integrator design which contribute to its low drift are:

1. Thermal insulation inside and sometimes outside the chassis to reduce the effects of drafts and heat from human contact.

2. Silica used inside the chassis to keep the electrical insulators dry.
3. Use of solder with a low thermal EMF, used not only in the construction of the integrator but also in any joints made in the search coil leads.
4. Running the integrator on battery power from rechargable battery packs.

Drift is trimmed with an input to the operational amplifier from a 100 kΩ voltage divider. Typical drift is less than 0.1 mV/sec with an input resistance of 1 kΩ and a search coil of negligible resistance.

Integrator reset is provided by an electronic (FET) switch which is activated by a +5 volt pulse. This allows the computer, or other circuits, to control the reset.

IV. APPLICATIONS

The facility has been used already in connection with the design of many magnets in the Main Accelerator and Booster. Measurements have been made in pulsed as well as DC operation. Quantities measured have included magnetic field B, remnant field, $\int Bdl$, gradient, as well as harmonic content of quadrupoles. Some of the more interesting applications are described here.

(a) Gradient measurements - An important measurement made in the design of both the bending magnets and the quadrupoles is that of field gradient. In the case of the bending magnets one is interested in the amount by which the gradient is different from zero, and in the quadrupoles one is interested in the amount by which the gradient differs from a certain fixed value. For both applications we use small, rectangular coil pairs[5] connected in opposition, with the difference output integrated.[6, 7, 8] A third, independent coil located in a fixed position in the magnet is used for measuring the excitation level. For measurement of gradient as a function of position the use of this coil is preferable to the use of a shunt, since the power supply for the magnet is rather noisy. This coil is also useful during DC operation, due to the drift in the power supply. At the time of each measurement the instantaneous excitation level is also measured and used to normalize the gradient measurement.

Figure 4 represents the organization in time of the data taken during pulsed operation. Figure 5 is a flow chart of computer operation during data taking. On the flat part of the current cycle (which represents the injection time of the synchrotron cycle) the coil pair is positioned by the probe-positioner and the integrators are automatically reset. On the rising part of the curve (representing the acceleration part of the cycle) the computer continuously digitizes the integrator outputs from the fixed coil and gradient pair. The latest and next latest sets of values are kept in two small arrays. (See Figure 5.) When the output of the integrator on the fixed coil reaches one of the values representing one of the desired current values, the previous and present current readings are stored and the computer goes on to wait for the next excitation level. After data has been stored for all desired current levels, the computer records the data on magnetic tape and positions the probe for the next reading. Operating in this fashion, we efficiently "use" each magnet pulse, while at the same time storing only useful data in memory and on the magnetic tape. Measurements during DC operation are easily accomplished in a similar manner. (In fact the same data taking programs are used simply by deleting the steps which cause the program to wait for current levels and the reset step.)

The analysis if, of course, carried out on the same computer and can be carried out as soon as one set of data has been taken. The programs for analysis, as well as data taking, are often stored on the same tape as the data, making it an unnecessary event to remount tapes. A tape is positioned and programs read in by a simple resident monitor routine. Figure 6 is a flow chart of a data reduction program for gradient measurements in a bending magnet. The desire value is k, where $k = \frac{1}{B}\frac{dB}{dx}$. A sample plotted output[9, 10] of this program is reproduced in Figure 7. (Axes and scales were added by hand.) In this figure the computer had plotted the k value under pulsed conditions at several values of the bending magnet field. The run was repeated ten times and there are ten values plotted for each value of x. The quantity plotted is $(k - k_o)$ vs x, where k_o is the apparent slopes of the field at $x = 0$. We have observed relatively small values of k_o, and they are believed to be due to such effects as imbalance between the coils in the gradient pair. The units of $(k - k_o)$ are meter^{-1}. Figure 7b shows measurements on the same model with a simulated vacuum chamber in place. The slope of k, or the sextupole, caused by the eddy currents in the vacuum chamber is clearly visible. The computer also made a least squares fit of k as a linear function of x over the central 1 inch in x and plotted sextupole as a function of B with and without the simulated vacuum chamber.

(b). Harmonic analysis of quadrupoles - We were able to do harmonic analysis on quadrupoles with a simple apparatus consisting of a rotatable set of coils mounted at two different radii. The coil assembly was rotated by a digital stepping motor under computer control, and data was taken in a manner similar to that just described. The Fourier analysis was carried out mathematically. The advantage of this method over the usual method of spinning coils connected to an audio-frequency analyzer is that no slip rings and no high-speed, non-metallic bearings are necessary. Also the phases of the several multipoles are obtained without any extra equipment. The individual harmonic analysis runs were Fourier analyzed on our computer. The data from many runs was read from our magnetic tape, analyzed, and averaged on the IBM 360/75.

The accuracy of the method was sufficient for putting upper limits of 0.2% on the multiple components from octupole through 20pole. Furthermore, by observing the sign of the octupole as a function of current, we discovered a flexing, as a function of current, of the poles in an early structural design of the Main Accelerator quadrupole.

(c) Precision mapping - Another application to be implemented is that of precision mapping the field of some magnets. The same standard lathe bed that we have used in the above measurements will continue to be used. While positioning of the carriage and cross slides is quite precise, small irregularities in the ways produces a wobble which is amplified by a long probe. This will be corrected by an automatic probe-tilting mechanism controlled by the computer. The method of sensing the probe tilt by means of an auto-reflecting laser and a mirror mounted on the probe mount has already been tested. The detector gives the tilt information in the form of voltages which are fed to the A/D converter. The motors will be controlled in the same was as the motors which are now used to position the carriage and slides. The auto-reflecting laser can easily detect tilt as small as 10^{-5} radian, which will make it possible to position the search coils to ± 0.001 inch.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the support and encouragement of Professor Frank Shoemaker during the design and construction of this apparatus. We want to thank Mr. Harry Barber for his excellent design contributions to the Moire-fringe probe mechanism.

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FIGURE CAPTIONS

Figure 1. Block diagram of the measuring facility.

Figure 2. Photograph of probe positioner No. 1. (No. 2 is at right.)

Figure 3. Circuit diagram of integrator (with built-in DC feedback amplifer.)

Figure 4. Data taking during magnet cycle.

Figure 5. Logic flow - data acquisition phase.

Figure 6. Logic flow - data reduction phase.

Figure 7. Measurements of bending magnet gradient.

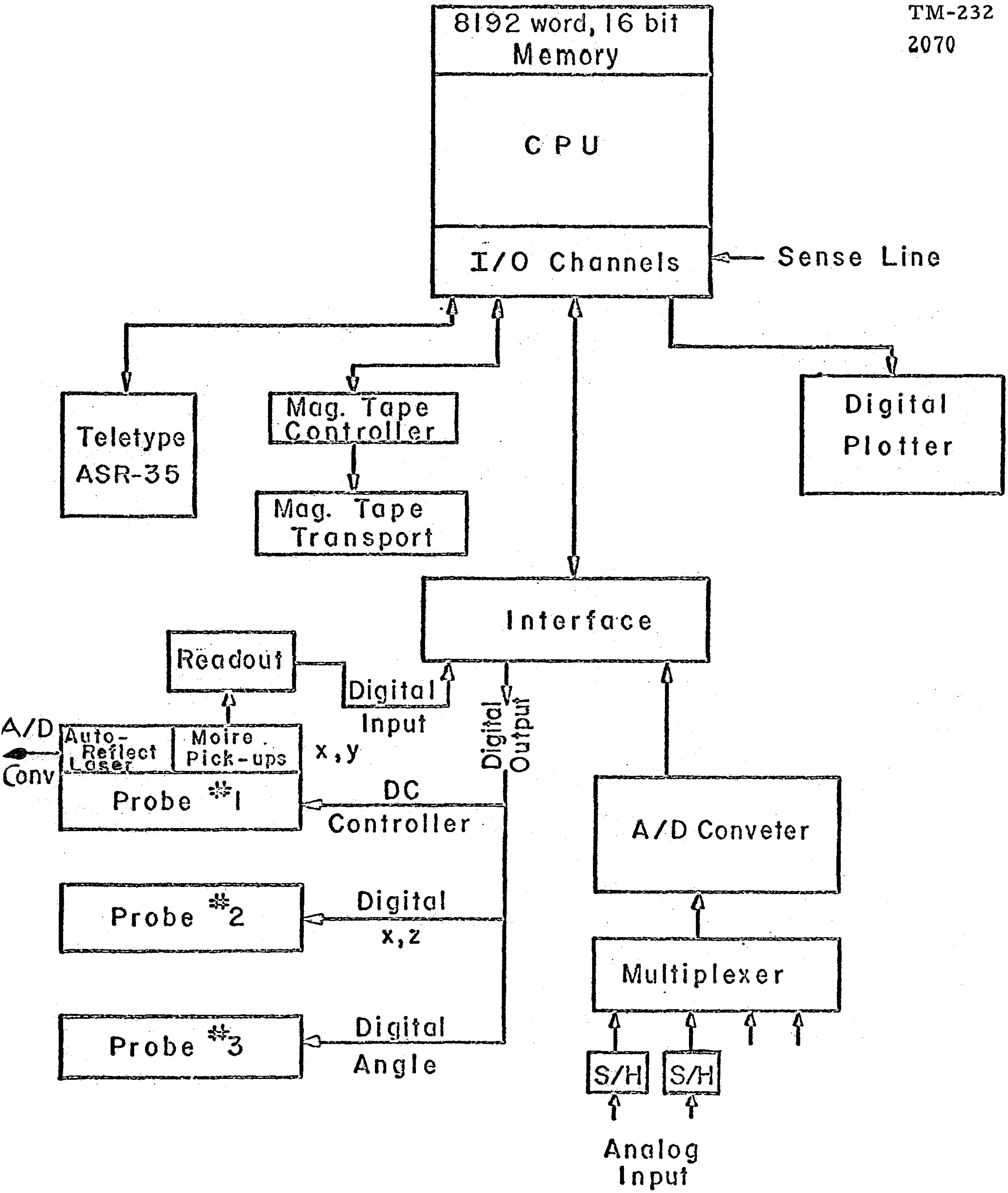


Figure 1. Block Diagram of the Measuring Facility

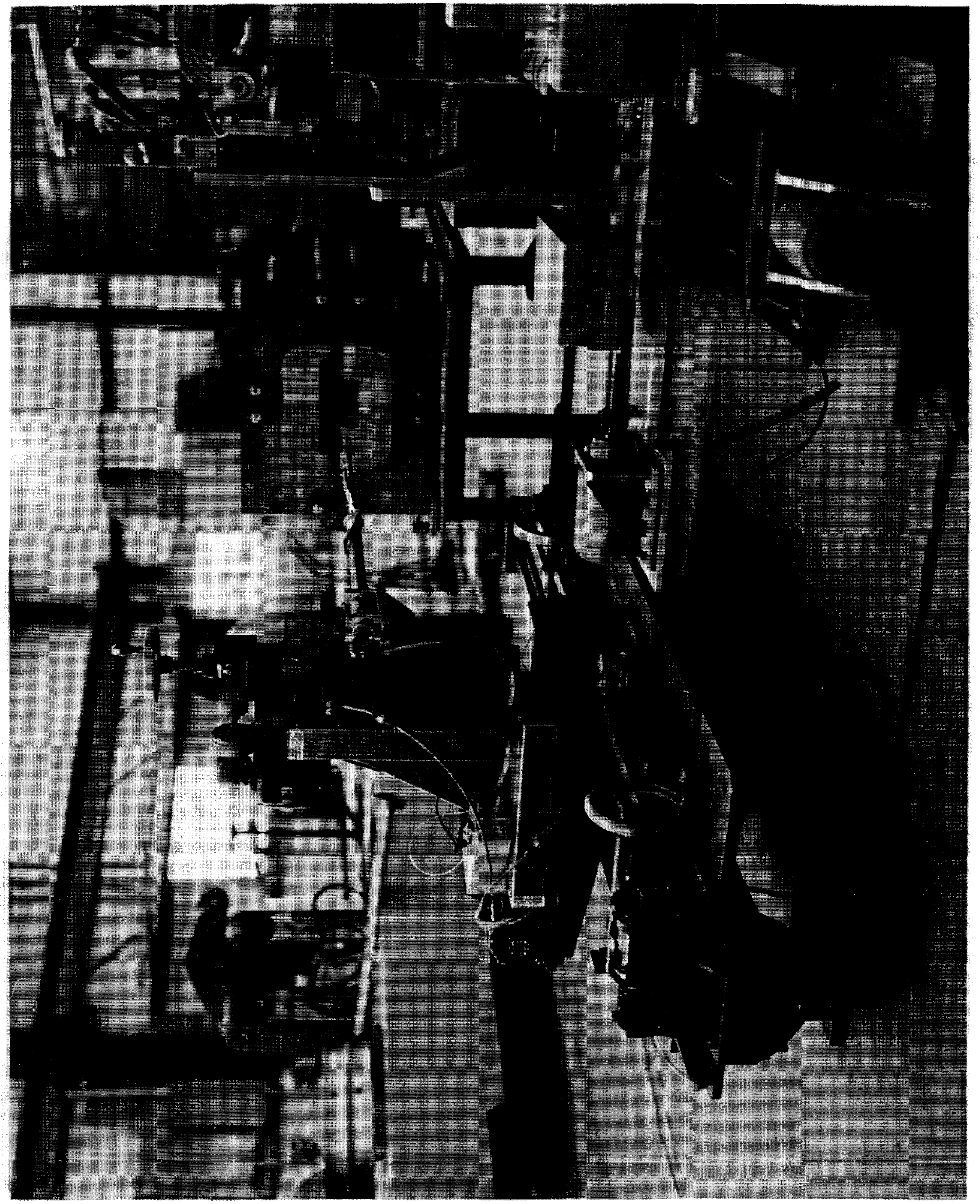
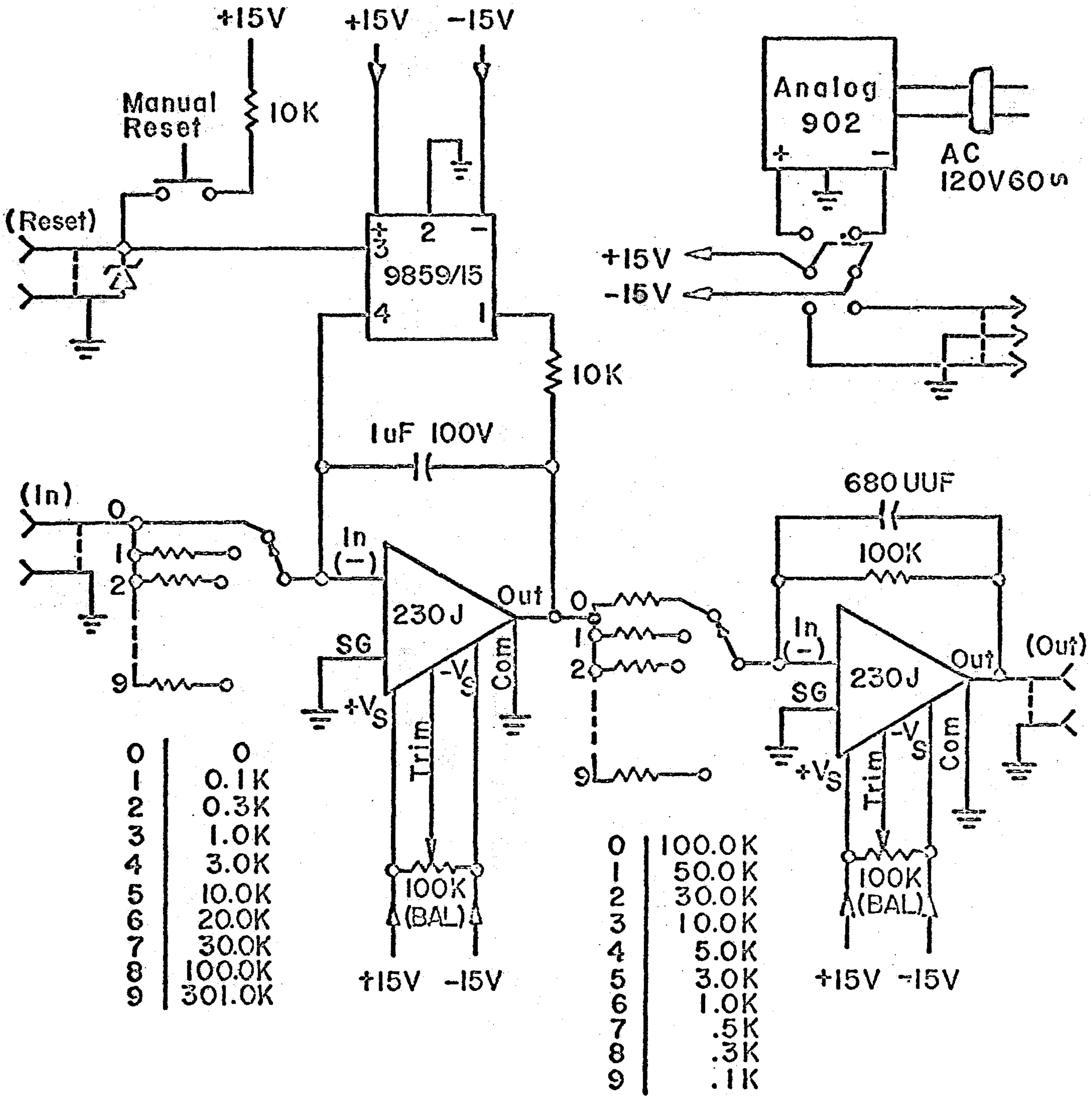


FIGURE 2



0	0
1	0.1K
2	0.3K
3	1.0K
4	3.0K
5	10.0K
6	20.0K
7	30.0K
8	100.0K
9	301.0K

0	100.0K
1	50.0K
2	30.0K
3	10.0K
4	5.0K
5	3.0K
6	1.0K
7	.5K
8	.3K
9	.1K

FIGURE 3

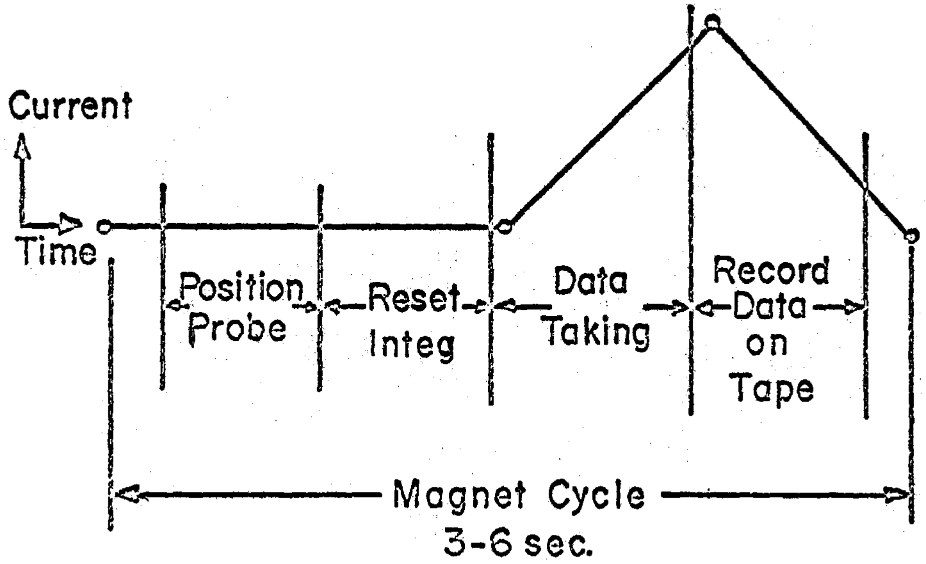

Current
Time
Position Probe
Reset Integ
Data Taking
Record Data on Tape
Magnet Cycle
3-6 sec.

FIGURE 4

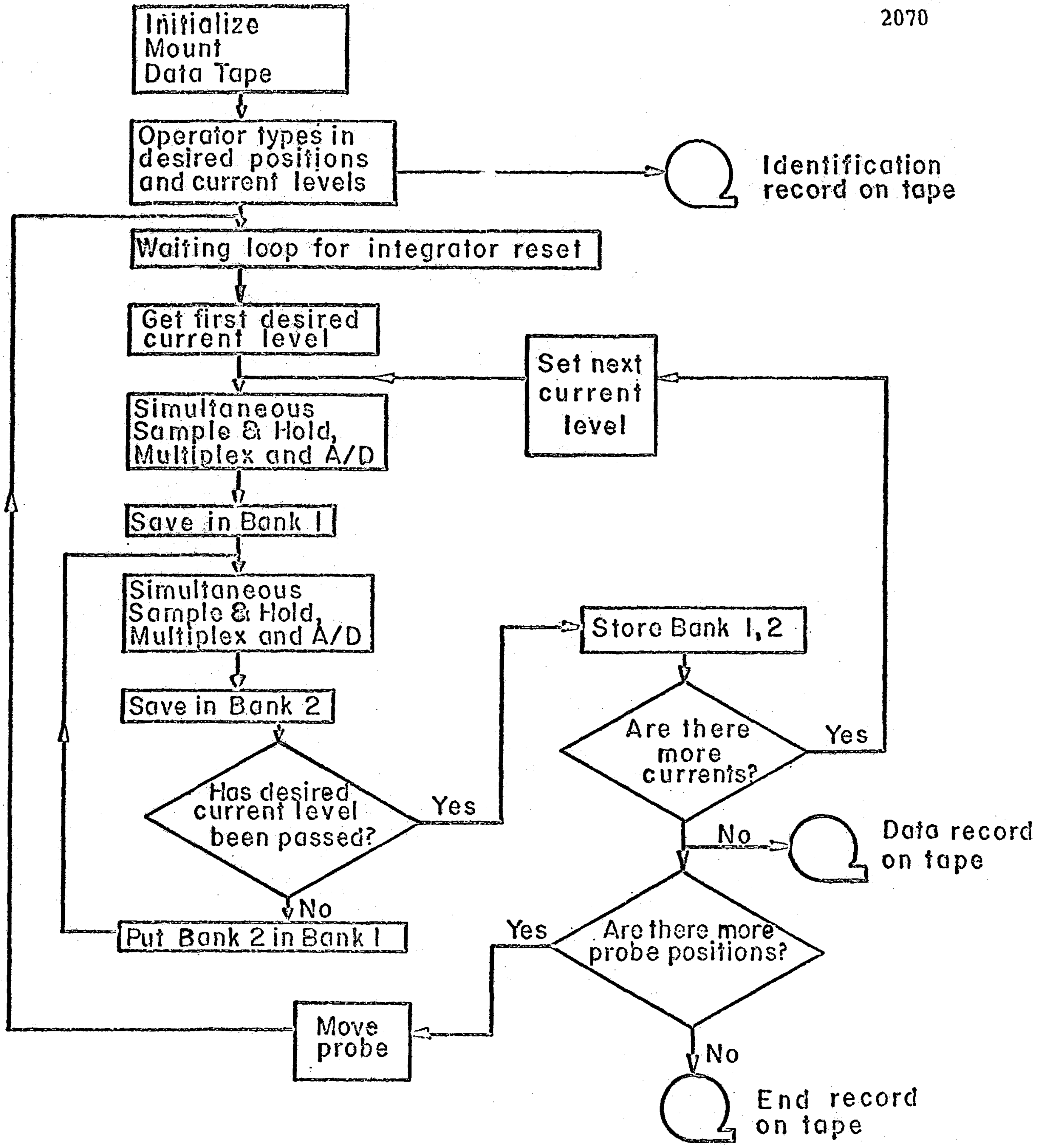

Initialize
Mount
Data Tape
Operator types in desired positions and current levels
Identification record on tape
Waiting loop for integrator reset
Get first desired current level
Set next current level
Simultaneous Sample & Hold, Multiplex and A/D
Save in Bank I
Simultaneous Sample & Hold, Multiplex and A/D
Store Bank I, 2
Save in Bank 2
Are there more currents?
Yes
Has desired current level been passed?
Yes
No
Data record on tape
No
Put Bank 2 in Bank I
Yes
Are there more probe positions?
Move probe
No
End record on tape

FIGURE 5

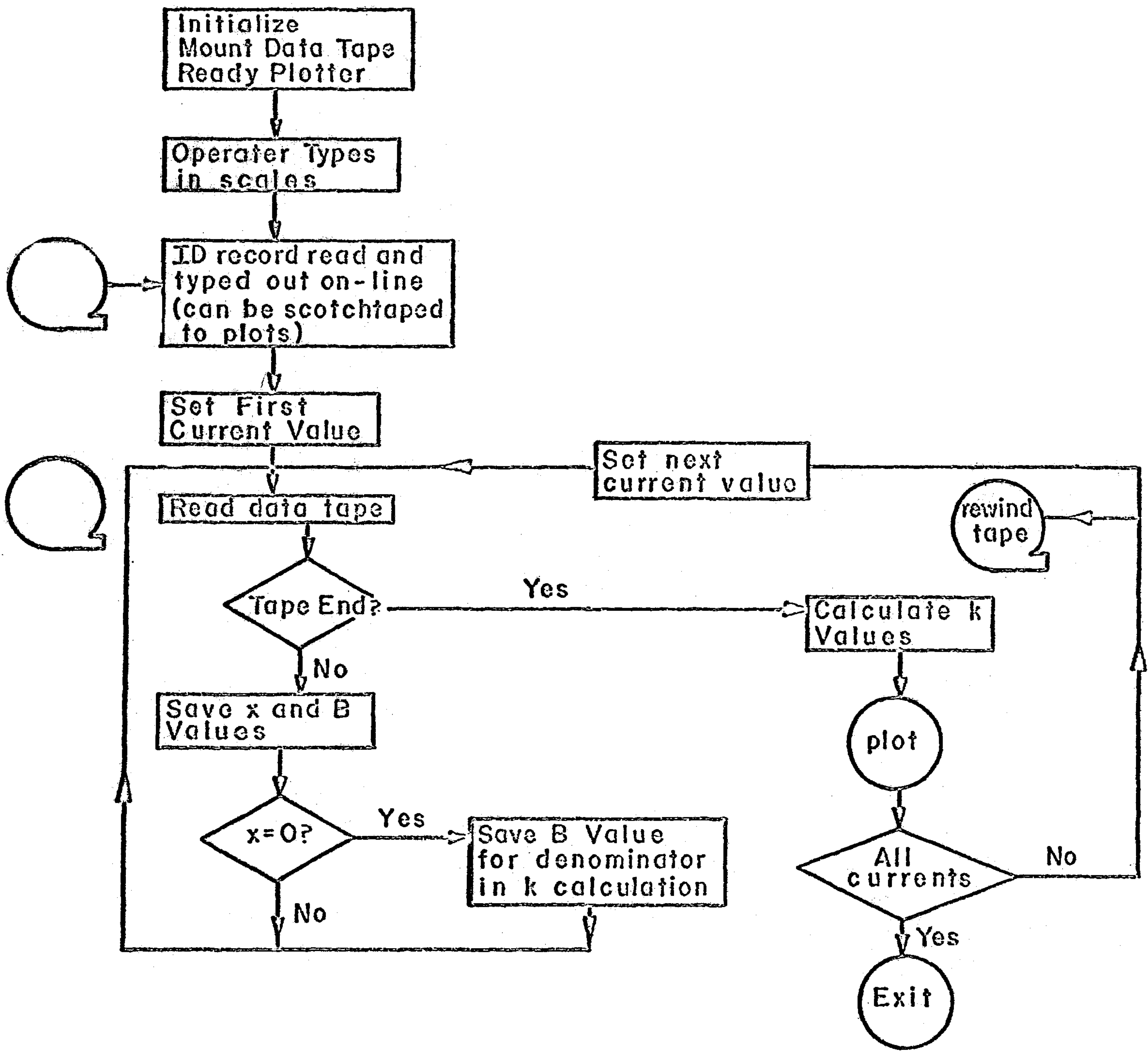

Initialize
Mount Data Tape
Ready Plotter
Operater Types in scales
ID record read and typed out on-line (can be scotchtaped to plots)
Set First Current Value
Set next current value
Read data tape
rewind tape
Tape End?
Yes
Calculate k Values
No
Save x and B Values
plot
x=0?
Yes
Save B Value for denominator in k calculation
No
All currents
No
Yes
Exit

FIGURE 6

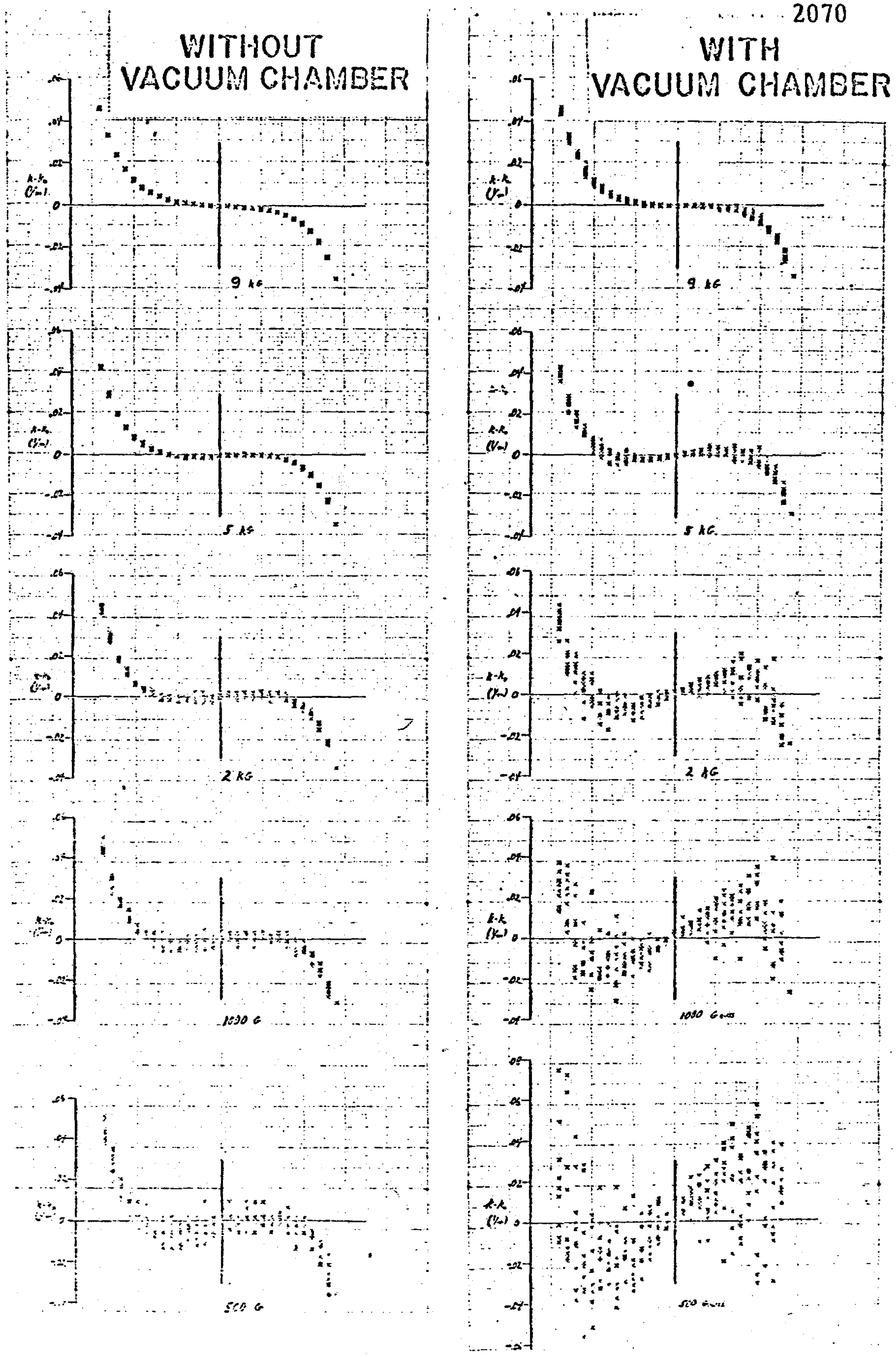

WITHOUT VACUUM CHAMBER
WITH VACUUM CHAMBER
k-k₀ (V-)
.04
.02
0
-.02
-.04
.06
9 kG
5 kG
2 kG
1000 G
500 G
1000 Gauss
500 Gauss

FIGURE 7