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THE REPRODUCIBILITY OF MAGNETIC FIELD SETTINGS WITH SOLID-CORED AND LAMINATED MAGNETS

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I. INTRODUCTION

It will be necessary to set the magnetic fields of the bending magnets for the beam transfer system of the Intersecting Storage Rings (ISR) reproducibly to within ± 1 part in 10^4 of pre-determined values. This should be done preferably by setting the excitation currents using a procedure which ensures the required accuracy and reproducibility in the field values. Experiments to find a suitable current setting procedure have been carried out with a solid-cored magnet and a laminated magnet. These experiments were done at different times with different equipment and are described, therefore, separately in this report.

II. EXPERIMENTS WITH A SOLID-CORED MAGNET

2.1 Experimental procedure

The solid-cored magnet was a standard 1 m bending magnet normally used for secondary particle beam from the CERN Proton Synchrotron (CPS). The excitation current for the magnet was supplied by a rectifier set (900 A,200 V) which had a short term instability of less than 1 part in 10^4. The current was measured to within 1 part in 10^4 with an accurate shunt (value 1 mΩ to within 1 part in 10^4 having a temperature coefficient of 2×10^{-5} per °C) and compensator. Magnetic fields greater than 1 kGauss were measured to better than ± 0.05 gauss by a nuclear magnetic resonance fluxmeter used in conjunction with a frequency counter. Residual field values, which were always less than 30 gauss, were measured to within 1 % using a commercial Hall plate gaussmeter.

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The rate of change of current could be varied between 1.3 and 4.6 A/sec by altering the sp ed of a small d- motor driving the control helipot of the power supply. Setting the current to within 1 part in 10^4 of a desired value was not possible with this arrangement, the precision being more like 1 part in 10^3. A negligible error is introduced, however, by extrapolating the result to the desired value of current. Thus, in the results given later, the rise in magnetic field is given for current increases from zero to 100.00 A, 190.00 A, 240.00 A and 320.00 A, each result being calculated respectively from readings with currents which were to within 1 part in 10^3 of each of the above currents.

For the bending magnets of the beam transfer system, the maximum field required will be 13 kGauss. For the bending magnet under test, which had a gap height of 11 cm, a field slightly greater than 13 kGauss was obtained when the excitation current was 340 A. Consequently, this was taken as the maximum current in the experiments. Most of the work was carried out with one type of current cycle which was investigated with different rates of current change. At the start of each cycle, the current was increased from 0 to 340 A then decreased to zero again at the rate of change under investigation, say K amp/sec. The residual field was allowed to stabilize ($\sim$ 12 min) and was measured. The following cycle was then investigated. The current was increased again at K amp/sec to within 1 part in 10^3 of say 100 A. Preliminary experiments had shown that having attained the final current, it required at least three minutes for the field to reach a stable final value. This was the case over the range of dI/dt values investigated (1,3 - 4,6 A/sec). Consequently, in general a 5 minute interval was allowed between the time the current was set and the time when accurate current and field readings were taken. In the case under discussion, the value of the field at 100.00 A was calculated from these readings. Thereafter, the current was increased to 340 A and decreased to zero again at K amp/sec and other currents e. g. 190.00 A, 240.00 A and 320.00 A were set randomly in the same way. From the repeat of field readings at a given current it was possible to see whether the differencesin the settings were greater than $\pm$ 1 part in 10^4. The same cycle was investigated at other values of dI/dt.

2.2 Results

The results of the investigations with the current cycle just described at various rates of current change are summarized in Table 1. The results for each current are grouped together but they were taken randomly with respect to those for other currents. It can be seen that for all cases the error in the reproducibility was less than ± 1 part in 10^4.

It can be seen also from Table 1 that the residual field is dependent on the rate of current decrease from 340 to zero amp. This is illustrated in Fig. 1 where the residual field is plotted against the time after reaching zero current. The rate of decrease from 340 to zero amperes is marked on each curve.

Similarly the increase in field from the residual value to that corresponding to a given excitation current depends on dI/dt. This is illustrated in Table 2, the data being obtained from the results of Table 1.

It can be seen that the faster the rate of current rise is, the larger is the increase in the field. This result is in agreement with those obtained by Cobb and Harris[1]. Also in agreement with their results is the relatively long time for the residual field to reach a steady value after switching off the current (see fig. 1). Both effects will be discussed later in this report.

Further investigations were carried out to see if it is necessary to wait for the residual field to have reached a stable value in order to be able to set the required field with an error in reproducibility of less than ± 1 part in 10^4. This was investigated by working with the same current cycle described previously but always with an excitation current of 190 A.

As previously, the results were extrapolated to the exact current of 190.00 A. After reaching zero current in the cycle, progressively longer times were allowed before starting to re-set the current of 190 A, e. g. 2 min., 4 min., etc. Initially, residual field readings at various times after the attainment of zero current had been recorded. The results are shown in Table 3.

TABLE 1

Rate of change of current	Residual field in gauss	Current I Amp.	Field in gauss with I Amp. excitation current	Error in reproducibility (parts in 10^4)
1,3 A/sec	12,2	100,00	4.088,6	± 0,5
	12,1	100,00	4.089,0	
	11,9	100,00	4.088,8	
	12,2	190,00	7.744,1	± 0,1
	12,0	190,00	7.744,2	
	12,2	240,00	9.733,3	± 0,2
	12,3	240,00	9.733,6	
	12,4	320,00	12.547,2	± 0,2
	12,3	320,00	12.547,8	
2,3 A/sec	10,3	100,00	4.089,1	± 0,5
	9,9	100,00	4.089,5	
	10,0	190,00	7.748,1	0
	9,9	190,00	7.748,1	
	10,3	240,00	9.735,8	± 0,1
	10,4	240,00	9.736,0	
	9,9	320,00	12.551,4	± 0,8
	10,4	320,00	12.553,5	
	9,6	320,00	12.552,3	
3,2 A/sec	8,35	100,00	4.088,5	± 0,4
	8,35	100,00	4.088,8	
	8,45	190,00	7.749,6	± 0,4
	8,3	190,00	7.750,2	
	8,5	240,00	9.739,4	± 0,5
	8,4	240,00	9.738,4	
	8,5	320,00	12.555,9	± 0,4
	8,35	320,00	12.556,9	

TABLE 1 (continued)

Rate of change of current	Residual field in gauss	Current I Amp.	Field in gauss with I Amp. excitation current	Error in reproducibility (parts in 10^4)
4,6 A/sec	7,35 7,15 7,1	100,00 100,00 100,00	4.088,7 4.088,4 4.088,7	± 0,4
	7,1 7,15	190,00 190,00	7.749,3 7.750,3	± 0,6
	6,95 7,1	240,00 240,00	9.741,4 9.741,8	± 0,2
	7,05 7,1	320,00 320,00	12.558,3 12.558,6	± 0,1

TABLE 2

Excitation current, I Amp.	Increase in field (gauss) from residual value when current increases to I Amp. at the following rates:			
	1,3 A/sec	2,3 A/sec	3,2 A/sec	4,6 A/sec
100,00	4.076,7	4.079,2	4.080,3	4.081,4
190,00	7.732,0	7.738,2	7.741,5	7.742,7
240,00	9.721,2	9.725,6	9.730,5	9.734,6
320,00	12.535,2	12.542,4	12.548,0	12.551,4

TABLE 3

Rate of current change = 3,2 A/sec

Time after reaching zero current (min.)	2	4	6	8	10	12	14	16	18	20
Residual field (gauss)	21	12,7	9,8	9,0	8,6	8,4	8,2	8,2	8,15	8,15

Time interval between zero current and starting to set 190 A (min)	2	4	6	8	10	14
Field at 190,00 A (gauss)	7.751,7	7.751,1	7.750,5	7.750,5	7.750,3	7.750,0

It can be seen from these results that the overall change in final field is 2,2 parts in 10^4. If 6 minutes are allowed before re-setting the current after reaching zero amperes the change is reduced to 0,65 parts in 10^4. The results after a waiting period $\geq$ 4 minutes agree to within $\pm$ 1 part in 10^4 with the earlier results of Table 1 for dI/dt = 3,2 A/sec where about 12 minutes was allowed for the value of the residual field to stabilize.

When further detailed design work is done on the power supplies for the magnets it may prove preferable to have a finite value of say 30 A as the minimum current instead of exactly zero amperes which may mean the use of circuit breakers as was the case with the power supply used for this experiment. With this point in mind, a further series of measurements were made with a minimum current of about 30 instead of zero amperes. Initially, the current was cycled 30 $\rightarrow$ 340 $\rightarrow$ 30 A and then the following cycle investigated:

$$30 \rightarrow I_1 \rightarrow 340 \rightarrow 30 \rightarrow I_2 \rightarrow 340 \rightarrow 30 \rightarrow I_1 \rightarrow 340 \quad \text{etc.}$$

where I_1 and I_2 were 100 and 190 A. Field and current measurements were taken about 5 minutes after setting these excitation currents and about 12 minutes was allowed with the current at 30 A. Again, these results were extrapolated to results at 100,00 A and 190,00 A which are shown in Table 4.

TABLE 4

Rate of current change = 3,2 A/sec

Excitation current	Field (gauss)	Error in reproducibility (parts in 10^4)
100,00	4.090,0	
100,00	4.090,5	
100,00	4.090,8	± 1
100,00	4.090,0	
190,00	7.748,6	
190,00	7.748,9	± 0,45
190,00	7.749,3	

It appears from these results, therefore, that it would be permissible to work with a minimum current of about 30 A.

From the results taken with the solid-cored magnet, it can be concluded that the magnetic field can be reproduced to within ± 1 part in 10^4 if the excitation current is reset accurately to 1 part in 10^4 using the current cycle described in section 2.1. It is clear, however, that in order to change from one required field value to another a total time of 6 - 9 minutes must be allowed. A considerable amount of this time is the 3 minutes necessary for the field to settle down to its final value.

It should be possible to increase the speed at which field settings are altered by using a laminated magnet in which eddy current effects are greatly reduced. The investigations with such a magnet are described below.

III. EXPERIMENTS WITH A LAMINATED MAGNET

3.1 Experimental procedure

It was not possible to obtain a suitable homogeneous-field, laminated bending magnet for these experiments so use was made of a laminated magnet with ahyperbolic pole profile which was available. This consisted of five of the original test blocks of the PS magnet and a special coil consisting of 192 turns. This magnet was also powered with a 900 A, 200 V rectifier set but in the present experiments the voltage across the shunt was measured with a digital voltmeter and not a compensator. A commercial Hall plate gaussmeter was used to measure the residual field to within 2 %. It was not possible to use the nuclear magnetic resonance fluxmeter to measure the high field values since the field gradient was much too large. Consequently, a thermally stabilized Hall plate was employed, the Hall plate current being supplied from a current stabilizing circuit and was stable to within 1 part in 10^4. The Hall voltage was measured with a second digital voltmeter. With this arrangement, it was possible to detect changes of 1 part in 10^4 in fields greater than about 6 kGauss.

One of the main purposes of working with a laminated magnet was to see how rapidly it is possible to set the required excitation current and still obtain magnetic fields reproducible to within $\pm$ 1 part in 10^4. Consequently, a different system of current setting was employed which was much faster and more accurate than the motor-driven helipot arrangement used previously. Such a system may also be more convenient for a remotely controlled power supply. The relevant circuit diagrams are shown in figs. 2 and 3. The control voltage applied to the rectifier was that established between G and H (fig. 2). A highly stable reference voltage (8 V) was applied to the terminals A and B. The relay contacts marked a_1, b_1, a_2, b_2, ... a_4, b_4 in figure 2 were operated by manually turning the switch S (fig. 3) to the positions 1, 2, 3 and 4 respectively. In any one position, the 8 V supply is connected across the appropriate potentiometer and the voltage across the capacitor C rises exponentially with a time constant RC. The final voltage across the capacitor and, therefore, the magnet's excitation current is determined by the setting of the potentiometer.

The current cycle investigated was established by moving S clockwise through the positions 0, 1, 2, 3, 4 and back to 0. In position 0 the magnet's excitation current was zero. On moving to position 1 a current I was established which was adjusted to be about 50 A by adjusting the setting of the potentiometer P_1. In the same way movement of S to positions 2 and 3 gave currents I_2 and I_3 which were adjusted to about 500 A and 50 A respectively. On moving to position 4, currents ${}_1I_4$ or ${}_2I_4$ could be obtained by using either potentiometer ${}_1P_4$ or ${}_2P_4$. In the present work ${}_1I_4$

was adjusted to about 390 A and $_2I_4$ to about 300 A.

3.2 Results

Experiments have been carried out with two values of RC viz. RC_1 = 4,7 seconds (R = 4,7 kΩ, $C_1 = 10^3$ μF) and RC_2 = 1,9 seconds (R = 4,7 kΩ, C_2 = 400 μF). The results of these investigations are similar and only those for RC_2 will be described in detail. The results using RC_1 are briefly summarized as follows. The current cycle described in section 3.1 was used in which 1 minute waiting times were allowed after switching to positions 1, 2, 3, 4 and 0. The field corresponding to position 4 (and currents $_1I_4$ or $_2I_4$ depending on the position of the switch S_1 in fig. 2) was found to show no appreciable lag behind the current, e. g. the current was within 1 part in 10^4 of the final value in 43 seconds while readings of the field taken every half minute showed it to be stable within 1 minute of switching to position 4. Reproducibility measurements were taken by repeatedly going through the current cycle using either the value $_1I_4$ or $_2I_4$ as the current corresponding to position 4. The field values corresponding respectively to $_1I_4$ and $_2I_4$ were found to be reproducible to within ± 1 part in 10^4. A similar result was obtained when the time for the complete cycle was shortened by reducing the waiting time at each of the positions 1, 2, 3 and 0 to 15 seconds. Again, the field values corresponding to currents $_1I_4$ and $_2I_4$ were stable within 1 minute.

In the faster cycle described above, the time required to change the magnetic field corresponding to one current, say $_1I_4$, to that corresponding to a different current, say $_2I_4$, is as short as 2 minutes. This was reduced even further by using the shorter time constant RC_2 of 1,9 seconds. A simple calculation shows that in this case the reference voltage between G and H of fig. 2 and therefore the current will be within 1 part in 10^4 of its ultimate value within 17 seconds. In order to see if there was any appreciable lag in the settling of the field behind that of the current, readings of the Hall plate voltage were taken at various times after switching to position 4 in the cycle. The results are shown in Table 5. The readings of the Hall plate voltage have not been converted into the equivalent values of the magnetic field because insufficient precise calibration data were available. It may be noted, however, that voltages of 206 mV and 157 mV correspond approximately to magnetic fields of 12,6 and 9,8 kGauss respectively.

TABLE 5

Readings of current and Hall plate voltage at various times after switching to position 4 in the current cycle. RC_2 = 1,9 seconds.

Time (min-sec)	0-20	0-30	0-40	1-00	1-30	2-00	3-00	4-00	5=00
${}_1I_4$ (A)	390.63	390.64	390.64	390.64	390.66	390.66	390.66	390.66	390.66
Hall plate volatag (mV)	206.15	206.17	206.17	206.15	206.15	206.15	206.15	206.17	206.17

Time (min-sec)	0-20	0-30	0-40	1-00	1-30	2-00	3-00	4-00
${}_2I_4$ (A)	299.96	299.98	299.99	299.99	299.99	299.99	299.99	299.98
Hall plate voltage (mV)	156.88	156.89	156.89	156.89	156.89	156.89	156.90	156.90

It can be seen from the results of Table 5 that the field values are constant to within ± 1 part in 10^4 20 sec. after switching to position 4 in the cycle.

A cycle was then investigated in which 10 second intervals were allowed after switching to each of the positions 0, 1, 2 and 3. In that time, the current corresponding to each position, therefore, reaches 99,5 % of its ultimate possible value. Readings of current and Hall plate voltage were taken 20 seconds after switching to position 4 in the cycle. The results are shown in Table 6.

TABLE 6

Order in which currents were set	$_1I_4$ (A)	Hall Plate Voltage (mV)	Error in reproducibility of field (parts in 10^4)	$_2I_4$ (A)	Hall Plate Voltage (mV)	Error in reproducibility of field (parts in 10^4)
1	390,63	206,15				
2	390,62	206,15				
3				299,96	156,88	
4			± 0,5	299,96	156,88	
5	390,62	206,17				0
6	390,61	206,15				
7				299,95	156,88	
8	390,61	206,15				
9				299,95	156,88	

It can be seen that the reproducibility in the settings of the current and the magnetic field are well within $\pm$ 1 part in 10^4. Further, the time to change from one working field value to another when using such a current cycle is 1 minute.

It is of interest to see whether the field in the laminated magnet depends in any way on the rate of rise of current to a given current. The mean results from the reproducibility measurements using RC_1 and RC_2 have been taken and normalized to 390,70 A (near to ${}_1I_4$ in each case) and 300,00 (near to ${}_2I_4$ in each case). These results are shown in Table 7.

TABLE 7

Normalized results obtained from the mean results of the reproducibility measurements.

RC (sec)	Time to complete 1 cycle	Hall plate voltage corresponding to ${}_1I_4$ (normalized to 390,70 A)	Hall plate voltage corresponding to ${}_2I_4$ (normalized to 300,00 A)
4,7	5 min.	206,19	156,91
4,7	2 min.	206,22	156,93
1,9	1 min.	206,19	156,90

It can be seen that the magnetic field at a given current is not significantly dependent on dI/dt for the cases investigated.

The results with the solid-cored magnet showed that the value of the residual field depended on the rate at which the current decayed to zero amperes. Similar investigations with the laminated magnet were made by measuring the field as a function of the time after switching from position 4 to position 0 in the current cycle, i. e. from ${}_1I_4$ to zero amperes. The field measurements were made with the Hall plate gaussmeter.

The decay of the fields after switching from position 4 to position 0 in the cycle is shown in fig. 4. Results with both RC_1 = 4,7 seconds and RC_2 = 1,9 seconds were taken, position 4 in the cycle corresponding to ${}_1I_4 \simeq$ 390 A. It can be seen from these results that the residual field is not significantly dependent on the rate of decay of current. Further, when the current decay curve has an RC time of 4,7 seconds, the field is within 1 gauss of the final residual field in 2 minutes; with RC = 1,9 seconds this is true after 1 minute.

IV. DISCUSSION

The relatively long time for the residual field in the solid-cored magnet to reach a steady value is not easily explained. The time for the field to stabilize to within 1 gauss of the final value is about 7 minutes whereas the time constant for the decay of current in the magnet's coils is about 4 seconds. Further, the time constant for the decay of eddy currents which could directly produce magnetic flux in the gap is estimated to be also about 4 seconds.

Ewing [2] first observed similar effects and in the later work of Richter [3] a well defined lag was observed in specimens of carbonyl-iron. Snoek [4] has demonstrated a close connection between magnetic lag and the impurities of carbon and nitrogen in the iron. He showed, for example, that with carbonyl-iron the effect disappeared when the carbon was removed by prolonged annealing in vacuum at high temperatures. Further, Richter's work with carbonyl-iron showed there was a close connection between magnetic and elastic lag, both effects obeying the same laws and having the same origin, i. e. the diffusion of carbon, nitrogen or other impurities at the temperature of the experiment. Also, theoretical work by Polder [5] has explained the elastic lag on the basis of the diffusion of carbon atoms in the iron and many of his predictions have been confirmed experimentally.

It is difficult, however, to see that these explanations of magnetic lag are applicable to the results of the present work which shows that the lag is considerably longer with the solid-cored magnet than with the laminated magnet. It is very unlikely that the slight differences in impurities that may be present in the steel of each magnet could account for the considerable differences observed in the magnetic lags. It is far more likely that the lag observed with the laminated magnet is shorter because of the fact that the magnitude of eddy currents is considerably reduced in the core of such a magnet. Some measurements by Brianti which have been reported by de Raad [6] show that closed loops of flux exist in the core of a magnet. Eddy currents associated with these would take a long time to decay in the case of the solid-cored magnet because of the high inductance L and low resistanceR(and, therefore, large time constant L/R) and may have an effect on the field values measured in the gap. These explanations, however, are without conclusive experimental proof and must be regarded as very tentative.

V. CONCLUSIONS

The main conslusion to be drawn from the experiments with the solid-cored magnet and the laminated magnet is that the magnetic field in both can be reproduced to within ± 1 part in 10^4 by accurately resetting the current to 1 part in 10^4 using the procedures described in this report. The time taken to change from one field value to another is considerably shorter with the laminated magnet. This is primarily due to the shorter time lag between the attainment of the final current and the attainment of the final field, e. g. not more than 3 seconds with the laminated magnet compared with 3 minutes for the solid-cored magnet. The present results show that with the laminated magnet it is possible to change from one field value to another in as short a time as 1 minute and still obtain the required reproducibility of ± 1 part in 10^4. This fact may be very significant if rapid changes are needed in the magnetic fields when working with particles of different energy, e. g. transferring particles to the external target Hall of different energy to those injected into the ISR.

The method of setting the excitation current of the magnet by using the output voltage of an integrator circuit as the control voltage for the rectifier has proved satisfactory and could form the basis of the remote control system. It should, in fact, be possible to modify the system so that the speed of the current setting procedure is increased. For example, when setting the required current the value of C could be automatically reduced after a time t = 2 RC ($\approx$ 4 seconds with the lowest RC time used in the present work). This would bring the current much more rapidly to its final value and, since there appears to be only a very small time lag between field and current for the laminated magnet, this would decrease the time to change from one field value to another.

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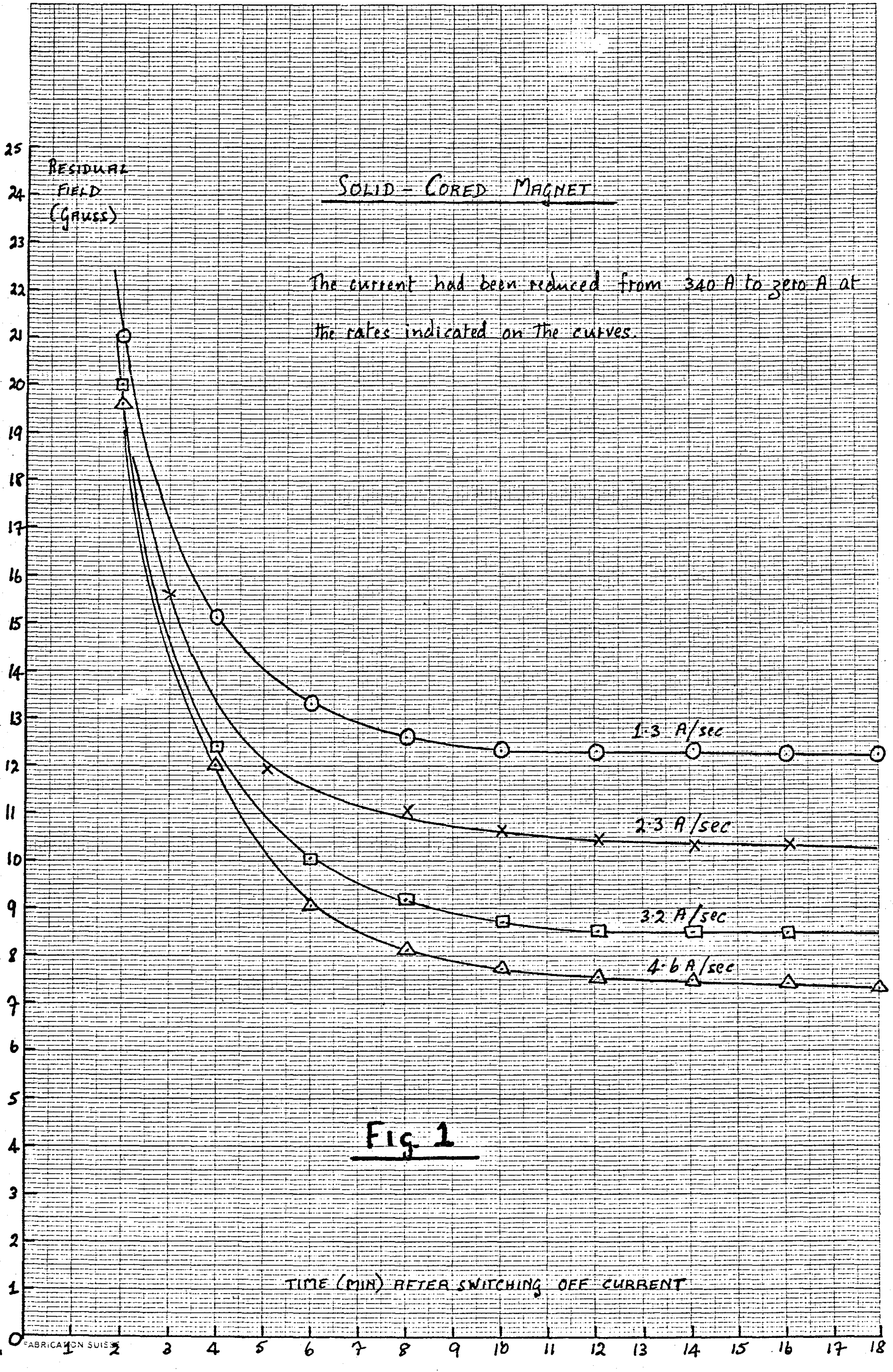

Fig 1

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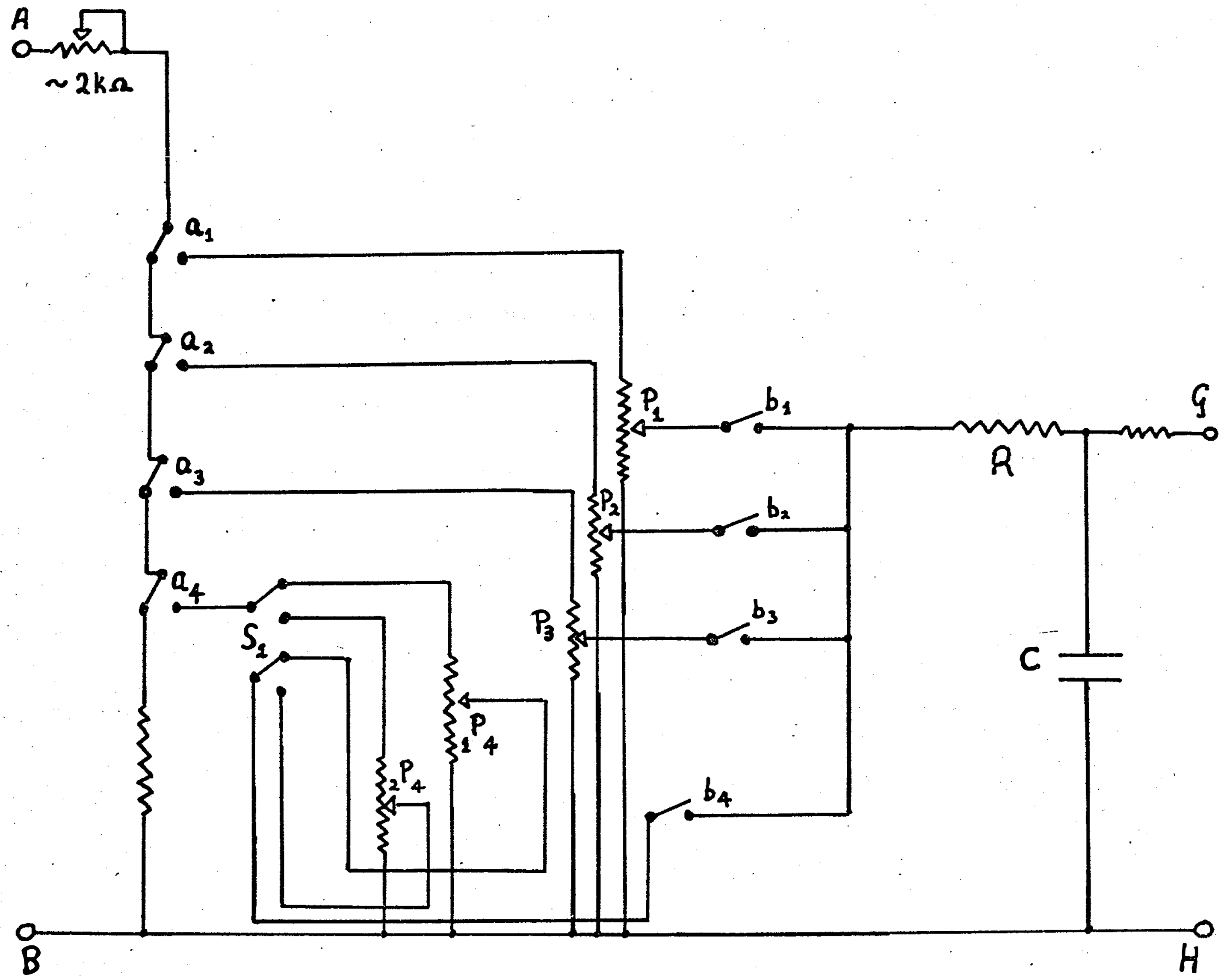
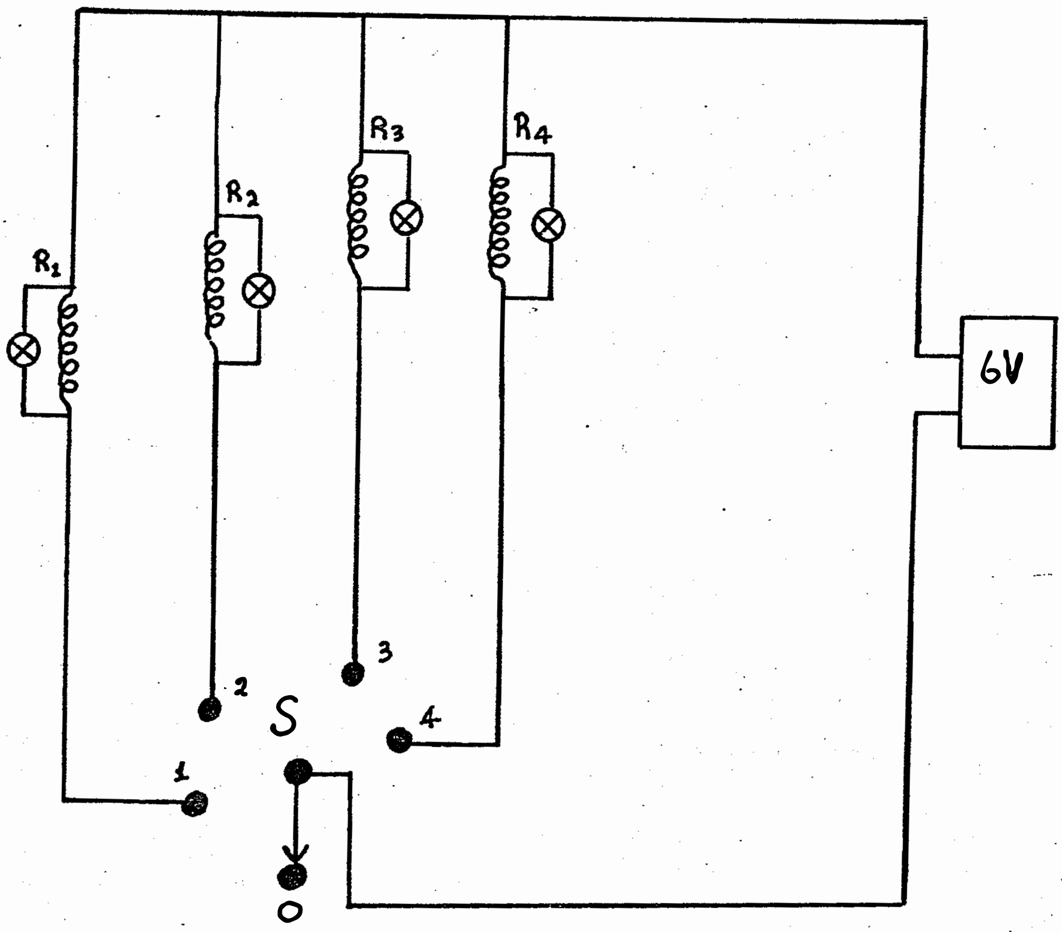


P_1, P_2, P_3, $_1P_4$ AND $_2P_4$ ARE 5 kΩ, 10 TURN HELIPOTS

DIAGRAM OF CIRCUIT USED TO ESTABLISH THE CONTROL VOLTAGE APPLIED TO THE RECTIFIER

FIG. 2



CIRCUIT DIAGRAM FOR RELAY EXCITATION

Fig. 3

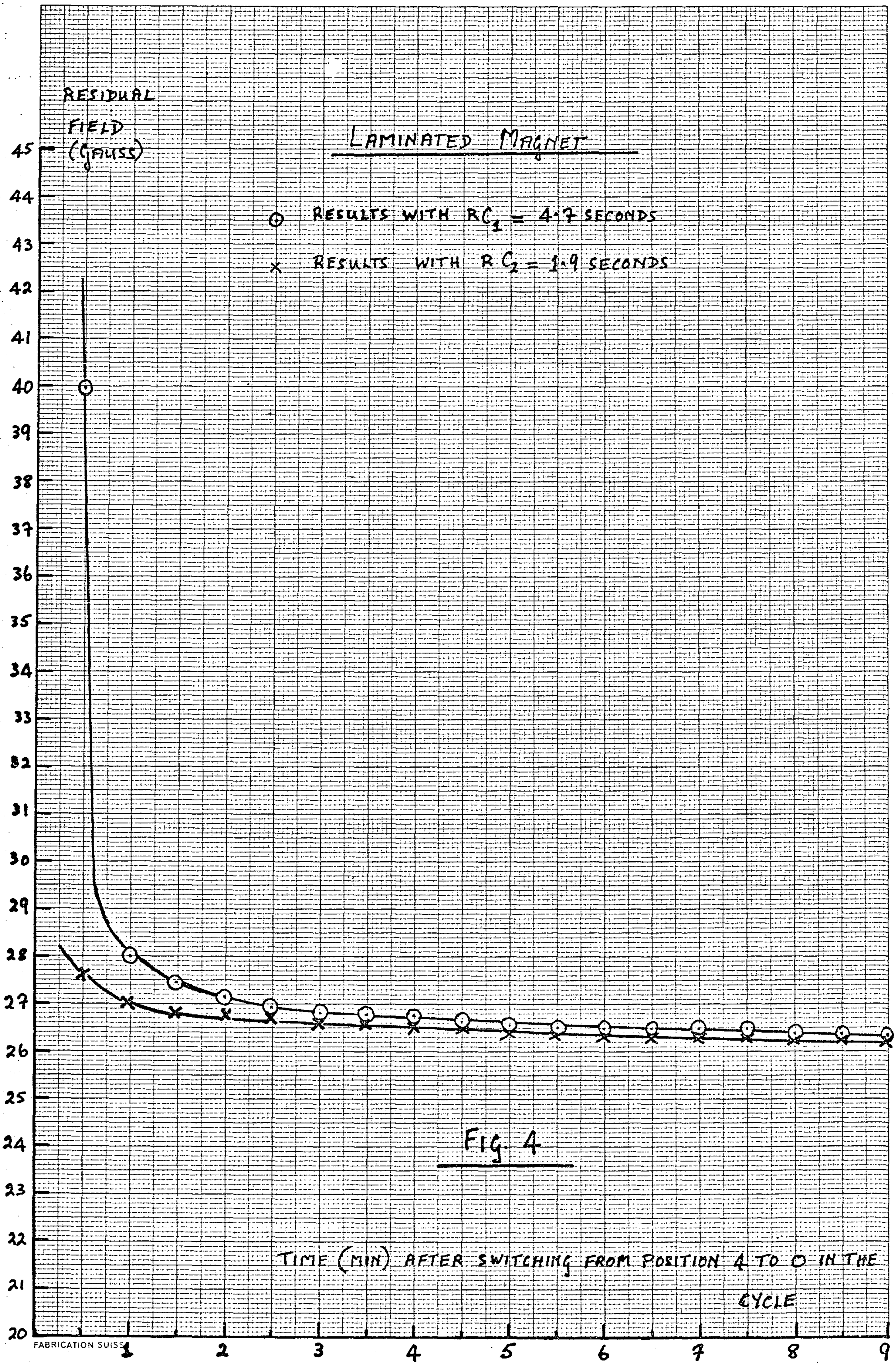

RESIDUAL FIELD (GAUSS)
LAMINATED MAGNET
RESULTS WITH RC1 = 4·7 SECONDS
RESULTS WITH RC2 = 1·9 SECONDS
TIME (MIN) AFTER SWITCHING FROM POSITION 4 TO 0 IN THE CYCLE
45
44
43
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FIG. 4