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A MAGNET CURRENT STABILIZER AND SCANNER FOR THE CEC MODEL 21-110 MASS SPECTROMETER

by

M.J. Mol

1968

Joint Nuclear Research Center
Ispra Establishment - Italy

Chemistry Department
Analytical and Inorganic Chemistry

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Furthermore, cyclic scanning by repetitive small linear variations in magnet current is possible.

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KEYWORDS

MASS SPECTROMETERS
RESOLUTION
CIRCUITS
MAGNETS
CURRENTS
STABILITY

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A MAGNET CURRENT STABILIZER AND SCANNER FOR THE CEC MODEL 21-110 MASS SPECTROMETER

1. INTRODUCTION (*)

The CEC model 21-110 mass-spectrometer is a double focussing instrument of the Mattauch-Herzog type with provisions for both electrical and photographic recording of spectra at high mass resolution.

For photographic recording the electric and magnetic deflection fields must be highly stable over extended periods, since fluctuations of the fields during an exposure displace the ion beams on the photoplate which causes a widening of the recorded mass lines and a reduction in mass resolution.

For electrical recording the magnetic deflection field must be scanned, preferably as an exponential function of time, and a wide range of scan-rates for both decreasing and increasing fields should be provided. Since some applications require the repetitive recording of a single peak or a small group of peaks, a means for cyclic scanning with variable width and cycle time is highly desirable.

In the 21-110 spectrometer the magnetic field is produced by an electromagnet with 4 identical coils and is stabilized or scanned by controlling the current through the coils. By means of a field switch, that selects either one or all four coils to carry the magnet current, two field ranges of 120-3000 Gauss and 480-12.000 Gauss are available. This renders it possible to control the current between 0,25 and 5 A and facilitates the stabilization.

The magnet current stabilizer and scanner supplied with the spectrometer contained a transistorized current stabilizer and a motor driven potentiometer in the reference circuit for scanning. The specified current stability ($\pm$ 20 ppm for a 20 minutes period) has been sufficient for the mass resolutions used. However, the scanning mechanism has caused serious troubles since it did not produce an even rotation of the potentiometer and the two selectable scan-rates of 0,0005 and 0,005 octaves/second were insufficient to cover all applications. Furthermore, the fact that cyclic scanning was impossible

(*) Manuscript received on August 14, 1968.

has been a serious handicap.

An improved version, available from the spectrometer manufacturer, uses a variable speed bi-directional motor driven scanning system that provides continuous adjustment of the scan-rate between zero and 0,02 octaves/sec. A relay operated timing circuit allows cyclic scanning with cycle times variable between 45 seconds and 7 minutes.

The magnet-current stabilizer and scanner described in this report features an improved current stability and an all electronic scanning circuit with a wide range of scan-rates eliminating the disadvantages of motor driven scanning.

2. DESIGN CRITERIA

2.1. Magnet current stability

If the deflecting fields are assumed to be perfectly constant the width W_L of a mass line, produced by monoenergetic ions of mass M travelling on a path radius R through the magnetic field, depends only on the size of the source slit and on the aberrations of the ion optical system. A small difference in mass ΔM will be accompanied by a difference in path radius.

$$\Delta R = \frac{R}{2} \cdot \frac{\Delta M}{M} \quad \text{(eq. 1), if } \Delta M \ll M$$

This difference in radius displaces the line over a distance ΔD on the photoplate. For the analyzer geometry in question the displacement

$$\Delta D = \Delta R \sqrt{2} = \frac{R\sqrt{2}}{2} \cdot \frac{\Delta M}{M} \quad \text{(eq. 2)}$$

The mass resolution, defined as the value $\frac{M}{\Delta M}$ for which ΔD equals W_L, is thus

$$P = \frac{R\sqrt{2}}{2\,W_L} \quad \text{(eq. 3)}$$

If the magnetic field fluctuates, a change ΔH in the fieldstrength H causes a difference in path radius

$$\Delta R' \approx R \cdot \frac{\Delta H}{H} \quad \text{(eq. 4), if } \Delta H \ll H$$

and an image displacement

$$\Delta D' = R\sqrt{2} \cdot \frac{\Delta H}{H} \qquad \text{(eq. 5)}$$

The effective width of the line is now

$$W_L' = W_L + \Delta D' \qquad \text{(eq. 6)}$$

and the massresolution is reduced to

$$P' = \frac{R\sqrt{2}}{2(W_L + \Delta D')} = \frac{P}{1 + 2\,P.\frac{\Delta H}{H}} \qquad \text{(eq. 7)}$$

A small variation ΔE in the electric field also displaces the image. This displacement is

$$\Delta D'' = \frac{R\sqrt{2}}{2} \cdot \frac{\Delta E}{E} \qquad \text{(eq. 8)}$$

and should be added to $\Delta D'$ to give the total line widening. Hence, the actual massresolution for fluctuating deflection fields is

$$P'' = \frac{P}{1 + P\left(2\frac{\Delta H}{H} + \frac{\Delta E}{E}\right)} \qquad \text{(eq. 9)}$$

The stability of the electric field in the 21-110 spectrometer is specified as 20 ppm for 20 minutes, but is actually somewhat better in our instrument. Mass resolutions of 15.000 are readily obtained with the present analyzer geometry and 25.000 could eventually be reached after minor modifications in the ion optical system.

Thus, to be sure that fluctuations in the magnetic field do not limit the mass resolution the magnet current stability should be $\pm$ 5 ppm for 20 minutes under normal laboratory conditions (temperature constant within 0,5°C).

2.2. Scanning

If mass dependent aberrations are neglected, the width W_L of the ion beams passing across the collector slit is constant throughout the spectrum and the duration T_b of an ion current peak depends only on W_L, the width of the collector slit W_c, and on the velocity V with which the beam moves across the slit.

For optimum utilization of the recording system bandwidth the peak durations should remain constant throughout the spectrum. This can only be realized by keeping the velocity V constant and requires the magnetic field to be varied as an exponential function of time. Thus,

$$H_{(t)} = H_o \exp. \left(\frac{t}{k} \right) \qquad \text{(eq. 10)}$$

and the mass M varies with time as

$$M_{(t)} = M_o \exp. (a.t.\ln 2), \qquad \text{(eq. 11)}$$

where $a = \dfrac{2}{k \ln 2}$ octaves in mass/second.

The scan-rate a and the mass resolution for electrical recording P_e determine the duration of the peaks, since

$$T_b = \frac{1}{Pe.\ a.\ \ln 2} \qquad \text{(eq. 12)}$$

For a given bandwidth of the recording system the acceptable amount of peak distortion determines the minimum tolerable peak duration T_b and therefore the maximum scan-rate at mass resolution P_e.

The use of a normal potentiometric strip-chart recorder requires a peak duration of at least 1 second, which means a maximum scan-rate of 10^{-4} octaves/sec.at a mass resolution of 14.000. On the other hand, a high-speed recorder capable of writing peaks with a duration of 1 m sec enables a spectrum with mass resolution 3500 to be scanned at 0,4 octaves/sec. It must therefore be possible to vary the scan-rate from 10^{-4} to 0,4 octaves/sec. for both increasing fields ($a > o$) and decreasing fields ($a < o$).

During cyclic scanning the centre value should not change upon varying the width or the duration of the cycle. Since cyclic scanning is used to cover a region of a few percent of the centre value an exponential function is not necessary and a triangular signal can be used instead.
Only a single peak or a pair of adjacent peaks are recorded during a cycle. Therefore, a range of adjustment from 4 to 60 seconds for the cycle period is sufficient.

3. MAGNET CURRENT STABILIZER AND SCANNER

3.1. General

The following points were considered in the design of the magnet current stabilizer and scanner.

a. The stability and scan-rate requirements as described in sec.2.

b. The unit must be an integral part of the mass-spectrometer and therefore be electrically and mechanically interchangeable with the original magnet current supply.

c. Operation from the stabilized power line in the spectrometer carrying 115 Volts $\pm$ 1% 50 Hz possible.

d. The 4 coils of the analyzer magnet have a resistance of 1,1 Ohms each and the inductance of the 4 coils in series is approximately 20 Henry. A resistor of 4 Ohms 160 Watts already present in the spectrometer can be used as a dummy for 3 coils.

3.2. Principle of operation

The control loop for the stabilization of the magnet current shown in fig. 1 . is conventional and consists of a series regulator SR 1, current sensing resistor Re, feedback-resistor Rf, input resistor Ra, and stabilizing amplifier A_1. If the open loop gain is much higher than $\frac{Ra}{Rf}$ an input voltage Ea will cause the magnet current to stabilize at a value such that the voltage drop across R_c is exactly equal to $\frac{Rf}{Ra}$. Ea. For constant current operation the voltage Ea is obtained from potentiometer R_r, connected to a highly stable reference supply.

For exponential scanning of the magnet current the voltage E_a is replaced by an exponentially changing signal E_t, obtained from the scan circuit. The exponential generator consists of a high gain differential amplifier with variable RC feedback in a well known and proven circuit (see fig. 2). Since point A, at exactly half the amplifier output, is connected to the inverting (I) input of the amplifier, the gain from the non-inverting (NI) input to the output is 2. In the "SCAN-RESET" position the NI input of the amplifier is connected to the potentiometer R_r through R_i and is kept at the level E_a since $R_i \ll R_k$. Consequently, the amplifier output is 2 E_a, and point A at E_a. The moment the circuit is switched to the "SCAN" position relay K_1 disconnects the NI input from R_r and because of the positive feedback network R_k C_k the voltage, at point A, will follow the exponential function.

$$E_t = E_a \cdot \exp.\left(\frac{2\ n\ -1}{R_k\ C_k} \cdot t\right) ,$$

where n is the fraction of E_{out} applied to R_k and $1 \geqslant n \geqslant o$.

Thus both the scanning direction and the time constant can be selected by merely chosing the value of the positive feedback factor n.

To prevent overloading of either the current regulator or the scan amplifier the exponential increase must be limited to a maximum. A level detector connected to the output of the scan amplifier triggers at a preset output level and energizes relay K_4 to disconnect R_k from the amplifier output.

For cyclic scanning the input of the stabilizing amplifier is connected to the reference voltage as for constant current operation. As shown in fig. 3, a triangular signal, applied to the summing junction of the stabilizing amplifier through R_b, is superimposed on the quiescent value of the magnet current. The triangle is generated by a circuit consisting of the scan amplifier, an integrating network, and the level detector. The desired waveform is obtained by the switching action of the level detector, that changes the position of relay K_4 each time the amplifier output exceeds a certain positive value or drops below a preset negative level.

3.3. Circuit description (see fig. 4)

3.3.1. The reference supply

Since the stability of the magnet current cannot be better than that of the reference voltage, the reference circuit has been constructed from high stability components with a low temperature coefficient. A full wave rectifier (D 13, D 14) followed by a choke-input filter supplies 130 Volts DC to a constant current generator (Q_4, D_9, D_{10}, R_{45}, R_{46}) which is loaded by a string of 4 zener diodes type 1 N 2824 to obtain a stable supply voltage for the final zener stabilizer. If potentiometer R_{45}, in the constant current generator, is adjusted for a current of 10 mA through the four 1 N 2824 diodes the temperature coefficient of the 36,6 Volts across these diodes is 5 ppm/°C or less. The series resistor (R_{42} - R_{44}) for the final zener stabilizer is composed of high stability resistors with a temperature coefficient of 5 ppm/°C and is adjusted to give a current of 7,5 mA through the zener diode 1N940. In this way a 8,9 Volts reference with a temperature coefficient of only 2 ppm/°C is obtained. A resistive divider (R_{40} - R_{41}) reduces the reference to a value compatible with the scan amplifier. The divider is loaded with a 10 turn potentiometer (R_{38}) and series resistor (R_{39}). The three resistors R_{40}, R_{41}, R_{39} are high stability types with equal temperature coefficients (5 ppm/°C) and are, together with the reference diode 1 N940, located in a thermally insulated box to shield them from draughts.

The divider resistance is made considerably smaller than the potentiometer resistance to reduce instabilities caused by their unequal temperature coefficients.

3.3.2. The magnet current supply and stabilizer

A full wave rectifier (D_{11}, D_{12}) and filter capacitor (C_7) deliver 49 Volts DC with an output resistance of approximately 2 Ohms and less than 8 Volts ptp ripple to the magnet current circuit, that consists of meter M_1, field switch S_1, magnet assembly L_1 through L_4 (or L_4 and dummy resistor R_1) , series resistor R_2, regulator transistors Q_2-Q_3, driver Q_1, and current sensing resistor R_4.

The magnet,dummy resistor R_1, series resistor R_2 and transient protector D_1-R_3, are located in or on the analyzer support of the spectrometer. The resistor R_2 of 2 Ohms has been installed to limit the power dissipated in the series transistors to 70 Watts maximum. However, resistor R_2 causes also a reduction in the maximum usable scan-rate, which becomes especially noticeable in the "HIGH" field range, where the presence of R_2 does not allow coverage of the entire current range at scan-rates higher than 0,15 octaves/sec. Faster scans up to 0,5 octave/sec are only possible by shorting out R_2, at the expense of an increased maximum power dissipation in the regulator up to 92 Watts.

The regulator transistors Q_2 and Q_3, of the type 2N 1412, are mounted on a radiator of such a size,that with natural convection cooling the maximum junction temperature is not exceeded for dissipations up to 72 Watts. Nevertheless,a tangential blower is installed to keep the I_{CO} of Q_2 and Q_3 below 50 mA even when R_2 is shorted out for high scan-rates.

Since the 4 terminal 0,1 Ohms current sensing resistor R_4 must be extremely stable, it has been especially wound from 2,4 mm^2 manganin, with a temperature coefficient of approximately 3 ppm/°C. To reduce the change in resistor temperature, upon raising the dissipation from 0 to 2,5 Watts, the entire resistor is contained in a brass cylinder of 7 cm diameter filled with silicon oil.

The stabilizing amplifier A_1, that drives the regulator transistors through driver Q_1, is a Burr-Brown model 1538 A epoxy encapsulated, chopper stabilized operational amplifier with a DC open loop gain of 160 dB and a unity gain bandwidth of 15 MHz. The low input voltage drift (1 μV/°C) and low offset current drift (2 pA/°C) keep the magnet current instabilities, caused by amplifier drift, at less than 2 ppm/°C or $\pm$ 6 ppm/24 hours at 5 A.

Although the amplifier itself can be operated with 100% negative feedback, because internal phase compensation prevents the gain to fall with frequency at more than 9 dB/octaves, the output impedance of the amplifier in combination with the collector to base capacity of transistor Q_1, and the low cut-off frequency of the regulator transistors, introduce an extra phase shift in the magnet current control loop, which causes oscillation at around 2 KHz.
An additional phase compensation network R_{11}-C_1 eliminates the tendency to oscillate. The values of R_{11} and C_1 were determined experimentally, as they should not reduce the AC loop gain more than required to prevent oscillation.
The feedback resistor R_8 and input resistor R_9 are high stability types with equal temperature coefficients (5 ppm/°C).

3.3.3. The scan circuit

The lowest scan-rate of 10^{-4} octaves/sec, equivalent to a time constant of 29000 seconds, should depend as little as possible on the leakage resistance of the scan capacitor and on the input resistance of the scan amplifier. Therefore, the Burr-Brown model 1556 FET differential operational amplifier is used, since this epoxy encapsulated unit provides an open loop gain of 100 dB, an input resistance exceeding 10^{11} Ohms, and an input offset current less than 5.10^{-11}A. The scan capacitor C_3 of 3,6 μF has been assembled from high quality, tubular, polystyrene capacitors, contained in a plastic dust cover. In this way, the time constant

of the capacitor amplifier combination is kept above 300.000 seconds.
Relays K_1 and K_2 connected to the NI input of the amplifier are reed-relays, with an insulation resistance of more than 10^{13} Ohms.

The scan selector S_2 has 5 positions, which are labelled "WIDE SCAN", "WIDE SCAN RESET", "OFF", "CYCLIC SCAN RESET", and "CYCLIC SCAN" in a clockwise direction.
In the "OFF" position the scan circuit is completely disconnected from the stabilizing amplifier. In the "WIDE SCAN RESET" position the scan amplifier output divider is connected to the stabilizing amplifier through S_{2a}. Switch sections S_{2c} and S_{2d} connect the scan amplifier as an exponential generator and S_{2e} energizes relay K_1 to hold the scan circuit at the starting level. Upon switching S_2 to the "WIDE SCAN" position K_1 becomes deenergized and the exponential scan starts.
The scan-rate selector S_4 provides 4 basic scan-rates in factors of 10. Switch S_3 changes the amount of positive feedback and acts not only as a scan-rate multiplier, but also as a direction selector ("UP" or "DOWN"). If during a scan in the "UP" direction the preset maximum is reached the level detector energizes relay K_4 which interrupts the positive feedback loop and holds the scan amplifier output at a level set by R_{19}.

In the "CYCLIC SCAN RESET" position the input of the stabilizing amplifier is connected to the reference supply through R_9-S_{2a}, and to the scan circuit through R_{13}-S_{2b}. Switch section S_{2d} connects the I input of the scan amplifier to the integrating network (C_2, R_{30} - R_{31}), and the positive feedback is switched off by S_{2c}. Section S_{2e} energizes K_2 to ground the NI input and clamps the level detector through D_{23} to hold K_4 deenergized. Since relay K_3 is still off, the integrating capacitor C_2 remains discharged through R_{29} and the integrating resistor is grounded.
With the system switched to "CYCLIC SCAN" K_3 becomes energized and integration starts with the amplifier output going positive. The linear increase continues till the level detector energizes K_4

which connects the integrating resistor to the + 15 Volts line. From that moment on, the amplifier output starts a linear decrease until the negative limit is reached and K_4 is deenergized by the level detector.
Switch S_5 and potentiometer R_{13} are the coarse and fine controls for the cycle width, whereas R_{30} controls the cycle period.

3.3.4. The level detector

The level detector consists of two complementary Schmitt-triggers (Q_{18} - Q_{19} - Q_{20} and Q_{21} - Q_{22} - Q_{23}) followed by a bistable circuit (Q_{15} - Q_{16}). The output of the scan amplifier is connected to the input of both Schmitt-triggers through the two back-to-back zener diodes 1Z 8,2. If the amplifier output increases above the zener voltage the NPN Schmitt-trigger switches and Q_{19} collector jumps from 0 to + 15 Volts. As a result Q_{17} sets the bistable to the ON position (Q_{15} conducting) which in turn causes relay K_4 to be energized through Q_{13}. As soon as the amplifier output becomes more negative than the zener voltage the PNP Schmitt-trigger switches, which resets the bistable to OFF and deenergizes K_4.
With the scan selector in either the "OFF", "WIDE SCAN RESET", or "CYCLIC SCAN RESET" position diodes D_{21}-D_{23} clamp the bistable in the OFF position to deenergize relay K_4.

3.3.5. The power supply

The operational amplifiers and the level detector need a supply of + 15 and - 15 Volts. Fluctuations in these voltages manifest themselves as a drift of 1,5 μV/% in the stabilizing amplifier. Therefore, the supplies must have a stability of at least 0,05%.
The -15 Volts are obtained from a conventional series stabilizer (Q_{5c}- Q_7) with a differential control amplifier and a temperature compensated zener diode 1N2166 as a reference.
Another series regulator (Q_{5a}- Q_6) delivers the stabilized + 15 Volts. Its control amplifier (Q_{11}- Q_{12}) utilizes the - 15 Volts

as reference to keep the two supply voltages symmetrical to common (ground).

An additional simple series stabilizer (Q_{5b})delivers the -12 Volts for the relays K_1 through K_4.

3.4. Mechanical construction

For mechanical compatibility with the mass-spectrometer the magnet current stabilizer and scanner has been constructed on a tilt-down chassis identical to that of the original magnet supply. The control amplifiers of the power supply, the level detector, the scan amplifier circuit, and the stabilizing amplifier are located on individual circuit boards. All other circuits are directly mounted on the vertical mounting panel that divides the chassis in two sections. The smaller of these contains the circuits that should operate at a temperature as constant as possible (zener circuits of the reference supply, stabilizing amplifier, scan amplifier, and control amplifiers of the power supply). The larger section contains the other circuits that are either not temperature sensitive or have a high power dissipation.

4. RESULTS OF A PERFORMANCE TEST

4.1. General

A performance test on the magnet current stabilizer and scanner was carried out with the unit installed in the mass-spectrometer and connected to the magnet circuit. All measurements were made under normal laboratory conditions and the results of the tests are therefore typical values rather than absolute limits.

The stabilities of the voltages and currents were recorded with a Hewlett-Packard model 3420 A/B differential voltmeter operated from an unstabilized 220 Volts power line.

The interpretation of the measurements is rather difficult since the stability of the voltmeter is not much higher than that of the unit under test. Therefore, the results should be correlated to the ambient conditions and the following voltmeter specifications.

- -**stability:** 1 ppm/hour or 5 ppm/24 hours
- -zero stability: 0,5 ppm/24 hours
- -Temperature coefficient: $\pm$ 1 ppm/°C
- -zero drift: 0,25 ppm/°C of full scale
- -line regulation: 1 ppm for a 10% line voltage change

Since these values are maximum limits, it is reasonable to assume an overall voltmeter stability of $\pm$ 1,5 ppm during 2 hours of recording at a constant ambient temperature $\pm$ 0,5°C and with line voltage fluctuations less than 5%.

4.2. The power supplies

Both the + 15 and -15 Volts supplies are capable of delivering 0,3 A, but under normal operating conditions the current load never exceeds 120 mA and load variations remain less than 100 mA.
With the outputs adjusted to within 0,2% of their nominal values the following performance was measured:

- -line regulation: better than 0,01% for a 10% line voltage change
- -load regulation: better than 0,01% for a 100 mA load change
- -Ripple : less than 1 mV ptp
- -stability : 0,01% for 2 hours

4.3. The reference voltage

The reference, used for the stabilization of the magnet current, is variable from 0,2 to 4 Volts $\pm$ 0,5%. The following test results apply to the maximum output of 4,008 Volts:

- -line regulation: 1 ppm for a line voltage change of 1%
- -ripple : less than 10 μV ptp
- -stability : $\pm$ 3 ppm for 2 hours
- -long term : $\pm$ 4 ppm for 12 hours

The stability was measured with the line voltage stabilized to 1%

and with ambient temperature fluctuations less than 1°C. A typical record of the reference stability made under these conditions is shown in figure 5.
The line regulation can be substantially improved by operating the constant current generator from a stabilized supply. However, this is not found necessary at present.

4.4. The magnet current

The magnet current is adjusted from 0,25 to 5 A by changing the reference voltage. A fine control over ± 0,5% of the actual setting is provided.
Repeated measurements of the current stability were made at different current settings and gave the following results.

-stability : ± 6 ppm over 2 hours at constant ambient temp.± 0,5°C.
-long term : ± 10 ppm for 12 hours at constant ambient temperature ± 1,5°C.

Since the voltage drop across the current sensing resistor was used to record fluctuations in magnet current, changes in the resistor, that is part of the control loop, are not included in the measurements.
Two records of the magnet current stability are shown in figures 6 and 7.

4.5. Scanning

The design values of the scan-rates for wide scanning are as follows:
scan-rate in octaves/second : 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}

multiplier : up: X 1, X 2, X 4, X 8
down: X 1, X 2, X 4, X 8

The values actually measured are shown in table I.

During cyclic scanning the cycle period can be adjusted from 3,5 seconds to 70 seconds, whereas the cycle width is continuously variable over the selectable ranges of 0,0015%, 0,015%, 0,15% and 1,5% of full scale current.

5. ACKNOWLEDGEMENT

The author thanks Mr. H. Laurent, head of the analytical and mineral chemistry, for his continuous interest in the subject.

Main Switch position in octaves/second	Multiplier-up				Multiplier-down			
	1	2	4	8	1	2	4	8
10^{-4}	$1,1 \times 10^{-4}$	$2,25 \times 10^{-4}$	$4,45 \times 10^{-4}$	$8,9 \times 10^{-4}$	$1,0 \times 10^{-4}$	$2,0 \times 10^{-4}$	$4,0 \times 10^{-4}$	$8,0 \times 10^{-4}$
10^{-3}	$1,2 \times 10^{-3}$	$2,24 \times 10^{-3}$	$4,45 \times 10^{-3}$	$8,9 \times 10^{-3}$	$1,03 \times 10^{-3}$	$2,06 \times 10^{-3}$	$4,1 \times 10^{-3}$	$8,2 \times 10^{-3}$
10^{-2}	$1,08 \times 10^{-2}$	$2,17 \times 10^{-2}$	$4,25 \times 10^{-2}$	$8,7 \times 10^{-2}$	$1,0 \times 10^{-2}$	$2,0 \times 10^{-2}$	$4,0 \times 10^{-2}$	$8,0 \times 10^{-2}$
10^{-1}	$1,06 \times 10^{-1}$	$2,1 \times 10^{-1}$	$4,2 \times 10^{-1}$	$8,6 \times 10^{-1}$	$1,0 \times 10^{-1}$	$2,0 \times 10^{-1}$	$4,0 \times 10^{-1}$	$8,0 \times 10^{-1}$

TABLE I

MEASURED VALUES OF SCAN-RATE IN OCTAVES/SECOND

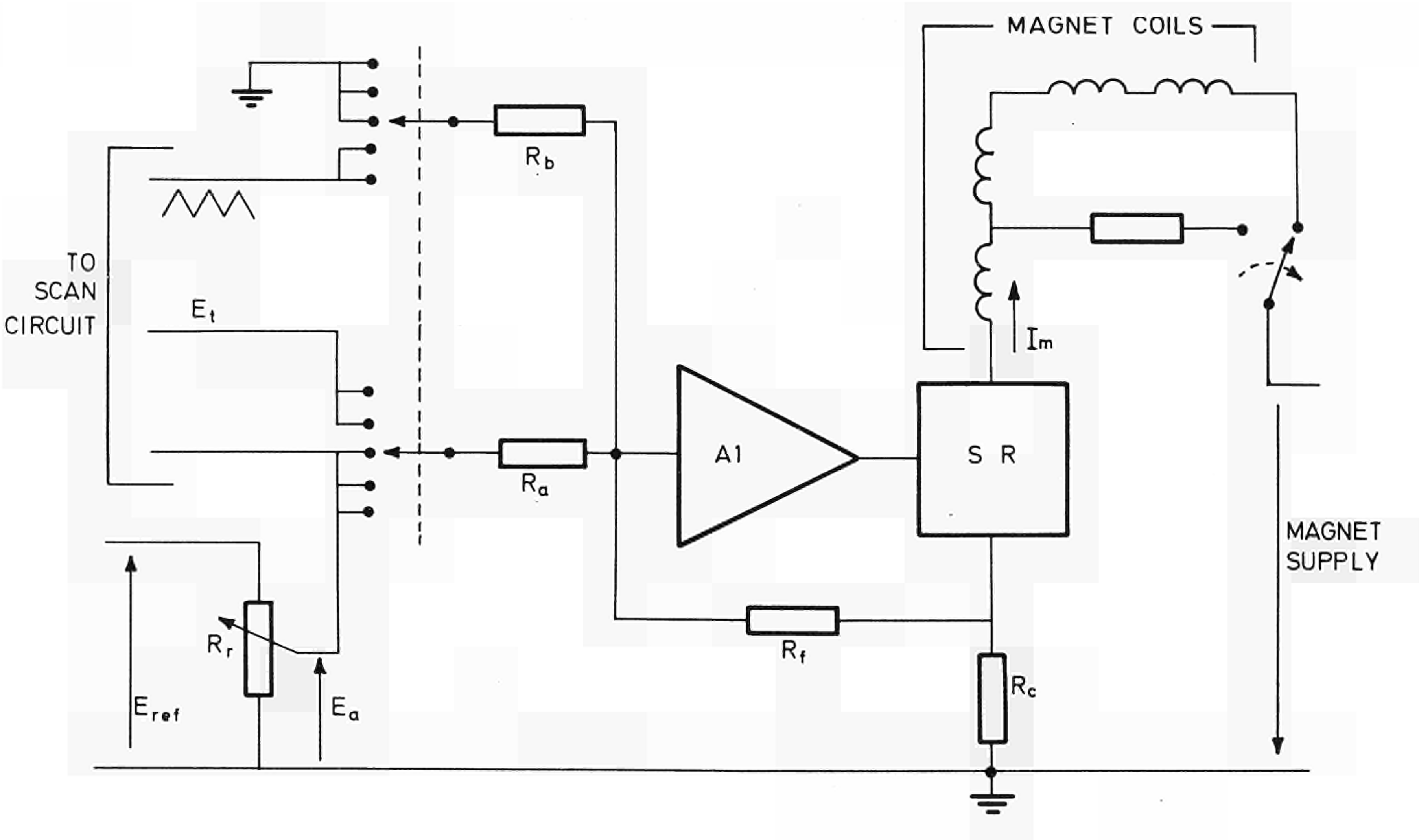


Fig. 1 MAGNET CURRENT STABILIZER
SIMPLIFIED CIRCUIT DIAGRAM

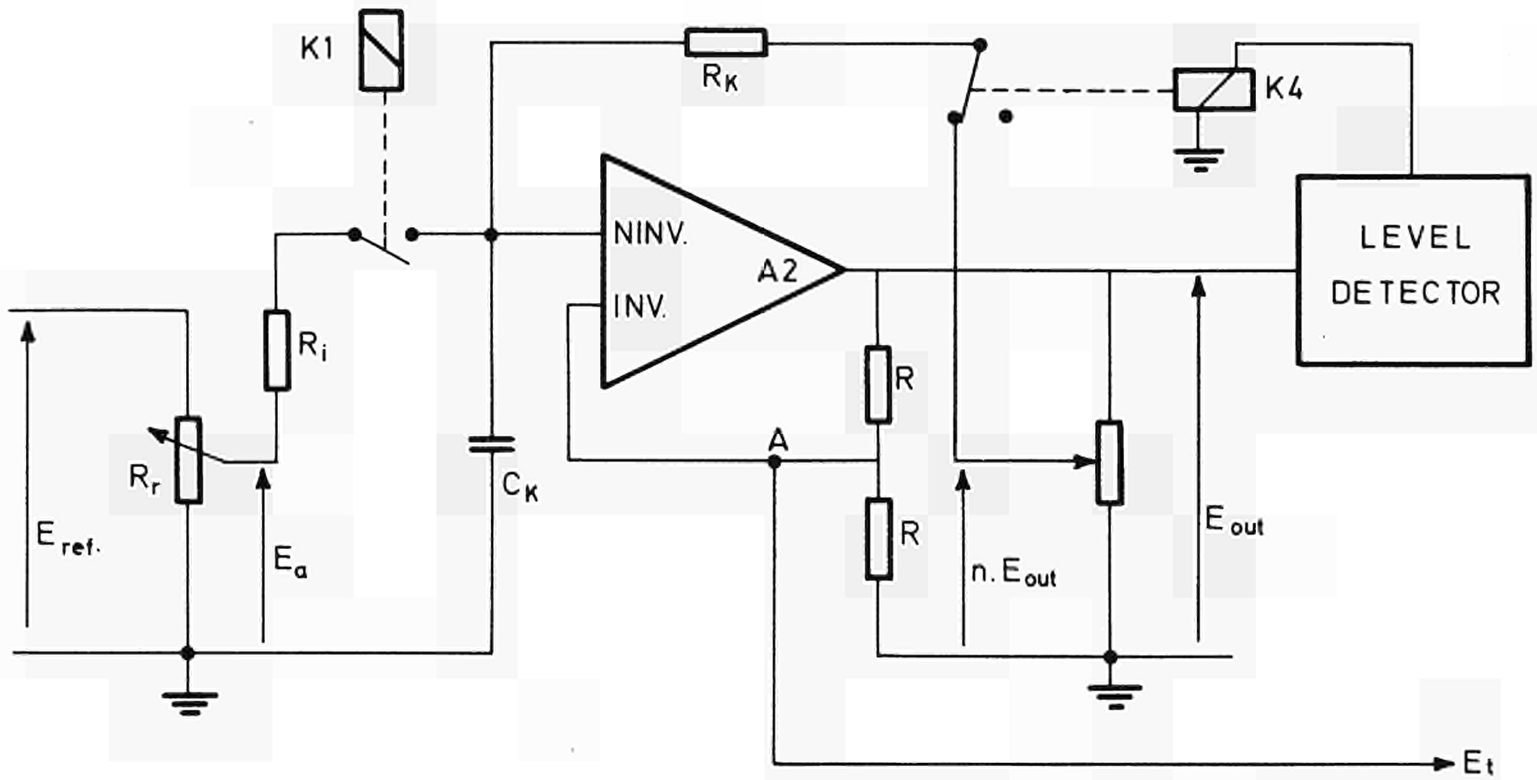


Fig. 2 SCAN GENERATOR FOR WIDE SCAN
SIMPLIFIED CIRCUIT DIAGRAM

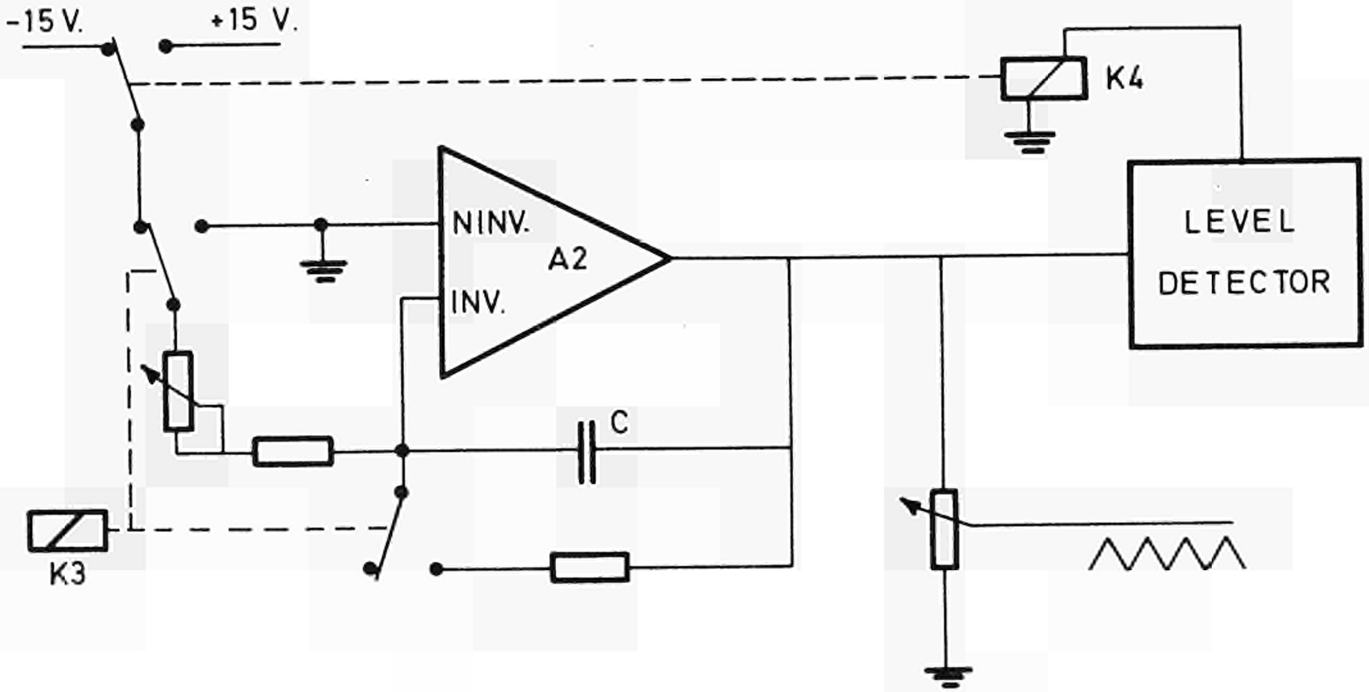
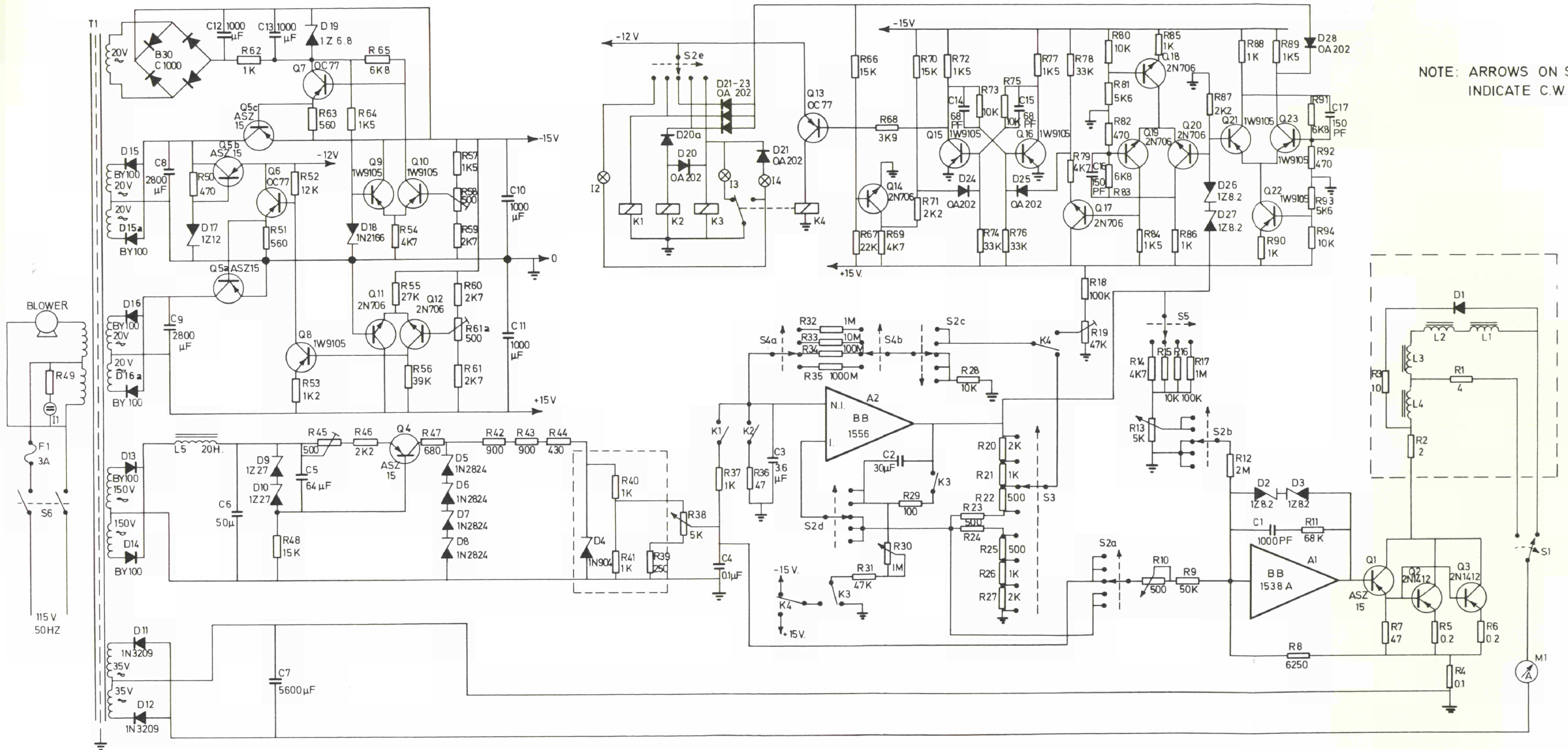


Fig. 3 SCAN GENERATOR FOR CYCLIC SCAN
SIMPLIFIED CIRCUIT DIAGRAM



NOTE: ARROWS ON SWITCHES INDICATE C.W ROTATION

Fig. 4 MAGNET CURRENT STABILIZER AND SCANNER, SCHEMATIC.

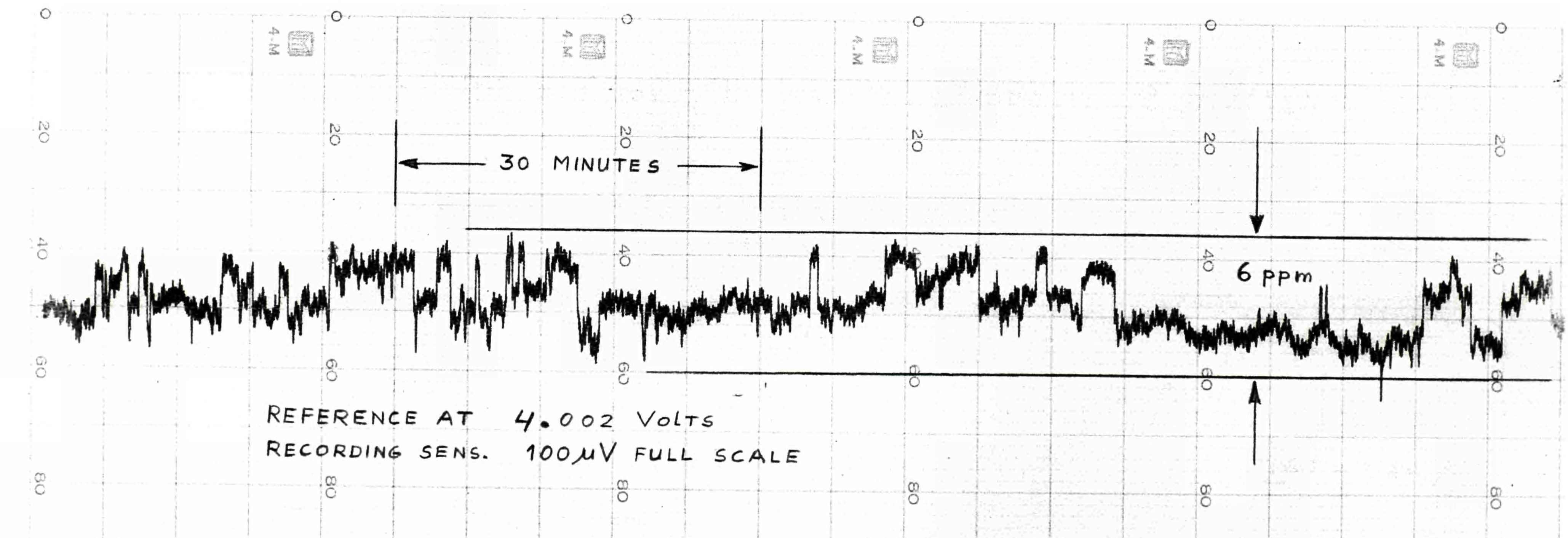


FIG. 5 TWO HOUR RECORD OF REFERENCE STABILITY.

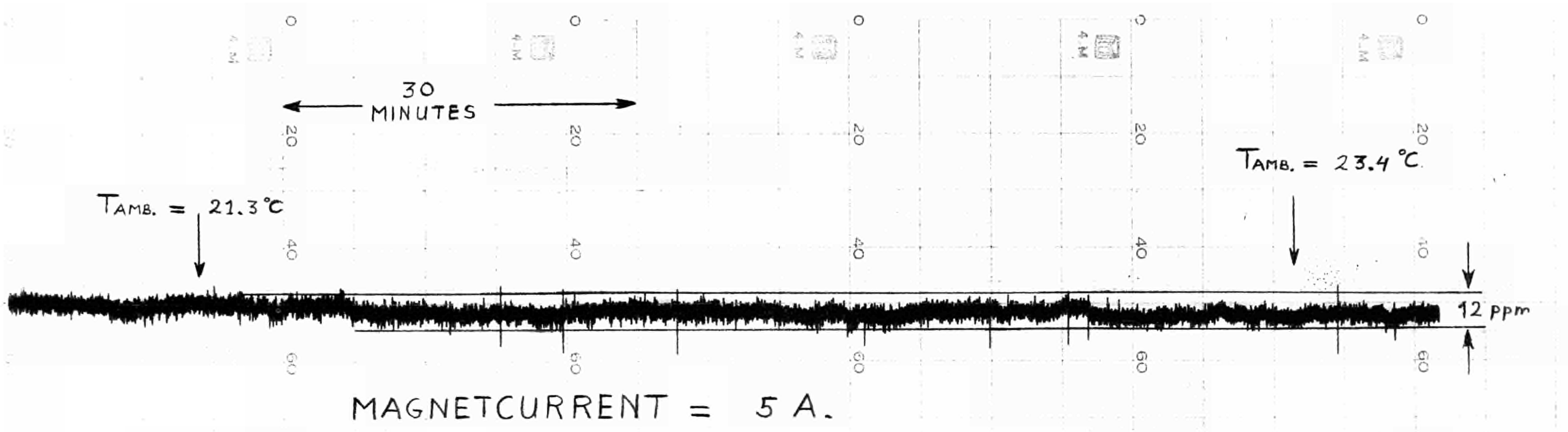


FIG. 6 TWO HOUR RECORD OF MAGNETCURRENT STABILITY.

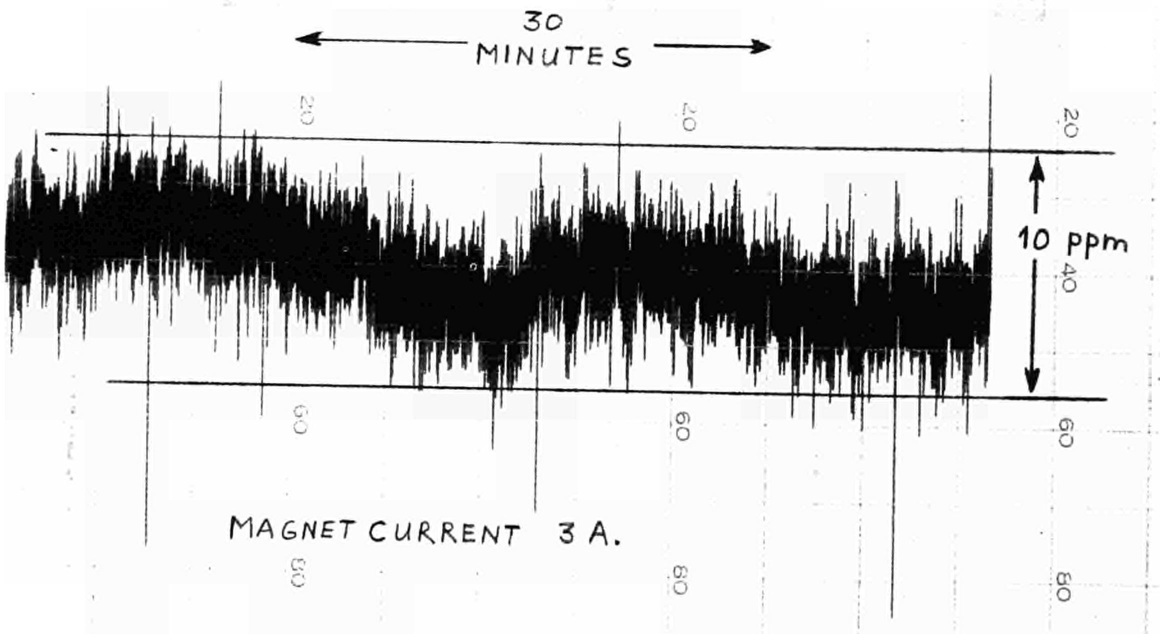


FIG. 7 RECORD OF MAGNETCURRENT STABILITY.

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Alfred Nobel

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