DESIGN, CONSTRUCTION AND STABILISATION OF A LARGE ELECTROMAGNET

by

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Yours sincerely,

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ABSTRACT

A seven and one half ton electromagnet has been built primarily for beam analysis in conjunction with the University of British Columbia electrostatic generator. With a current of 49 amperes, a field in excess of 19,900 gauss over an area of 256 square inches has been obtained across a one inch air gap. The hysteresis loop is satisfactorily small, being 0.2 amperes wide at a magnetising current of 15 amperes.

Current stability with the magnetising current varying from zero to 35 amperes has been maintained to a few parts in 10,000 over periods as long as seven hours.

Field stability has been checked using a proton resonance signal to be one part in 10,000 over a short period of eight minutes, and to be three parts in 10,000 over the long period of seven hours.

Using the stabilising system, the time required to change the field to a new setting is less than three seconds.

ACKNOWLEDGEMENT

Acknowledgement is given to the National Research Council for their bursary, and to the Defence Research Board for the grant in support of this research work.

Thanks are due to Dr. J. B. Warren of the Physics Department of the University of British Columbia for the help and guidance in initiating and carrying out this project.

D. A. Aaronson

September, 1950

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INTRODUCTION

The primary consideration in the design of a large electromagnet is to get the largest field reasonably possible with an iron core (upper limit about 20,000 gauss) over the pole area required for the least cost. The cost naturally depends on the pole faces and size of air gap which are chosen for the specific uses to which the magnet will be put. However, the size of the magnet is governed also by the type of coils, especially by their ability to dissipate the heat generated in them, as well as by the kind of iron and type of iron circuit used. These settle the window area required for the coil which in turn dictates the dimensions of the iron of the magnet. Since the cost of the magnet increases with the size and weight, with due regard to the relative cost of copper and iron, the best design hinges on maximum weight economy. This economy depends on whether more iron and less copper or more copper and less iron can be used. Again, the leakage factor increases with increasing dimensions, especially of the air gap [1, 2], therefore, the smaller the magnet, and air gap, the larger the percentage of useful flux.

The minimum size of the magnet is governed by the saturation in the iron used, which saturation usually occurs first in the iron just behind the pole pieces. Preliminary calculations on the minimum path length and magnetomotive force for the air gap, with a minimum window area assumed from experience, give a tentative size for the magnet. Computations on the size of the coil needed may then be made by a few successive approximations, once the type of power supply has been decided upon. Then, if the particular coil cannot radiate the power dissipated with a reasonable temperature rise, a larger coil, more turns, fewer amperes, but the same ampere-turns must be tried. With this, the calculations are repeated for the larger window area and length of iron path now needed. It is seen, then, that the best overall design depends a great deal on adequate and efficient heat transfer from the coils.

There is a choice of air cooling, forced ventilation[3], water or oil cooling. Different types of insulation on the coils also allow higher ambient working temperatures. Water cooling which is the least expensive and conserves most space and asbestos covering on the coils were finally chosen for this electromagnet.

A one quarter scale model was made up and its behaviour and field distribution checked, but it was not possible on such a model to check the coil design which therefore was rather conservatively rated in regard to heat dissipation and working temperature. However saturation characteristics were checked on the model using short pulses of current.

Following this, the seven and one half ton electromagnet was designed by members of the Physics staff of the University of British Columbia[N] after careful consideration had been given to all the above factors. It was to supply a field of at least 15,000 gauss over an area of 16 inches square across an air gap of one inch and to do so at a total cost of about $5,000.00. The design made use of an ingeneous method of winding the coils to conserve space and at the same time to provide adequate water cooling.

The design was found to be quite conservative. A field of over 19,900 gauss was obtained with a magnetising current of close to 49 amperes and a power of about 11 kilowatts. The total cost was near the figure stated above.

The magnet yoke and pole pieces were made by Messrs. Colville of Glasgow for about $3,000.00; the coils were made by Canadian General Electric for about $1,000.00. The Stabilization equipment has cost about $1,000.00.

[N] Dr. J. B. Warren and Mr. F. Bowers carried out most of the calculations. Mr. T. Mouat assisted in the engineering aspects of the magnet and coils.

In the first instance to achieve the energy resolution required, it was decided to stabilize the magnetising current to the required precision and check the variation in the magnetic field using a proton resonance method. Finally it is intended to stabilize the field itself using the proton resonance output.

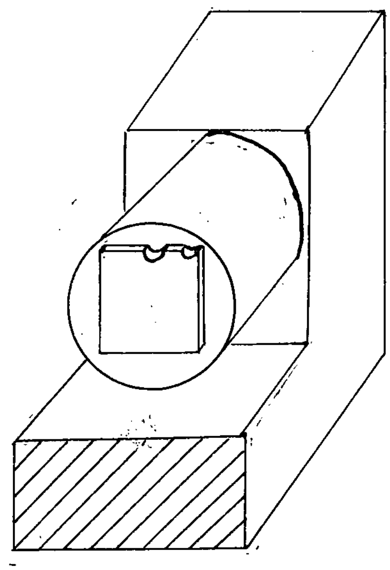

Fig. 1.

Cut-away perspective view of the magnet

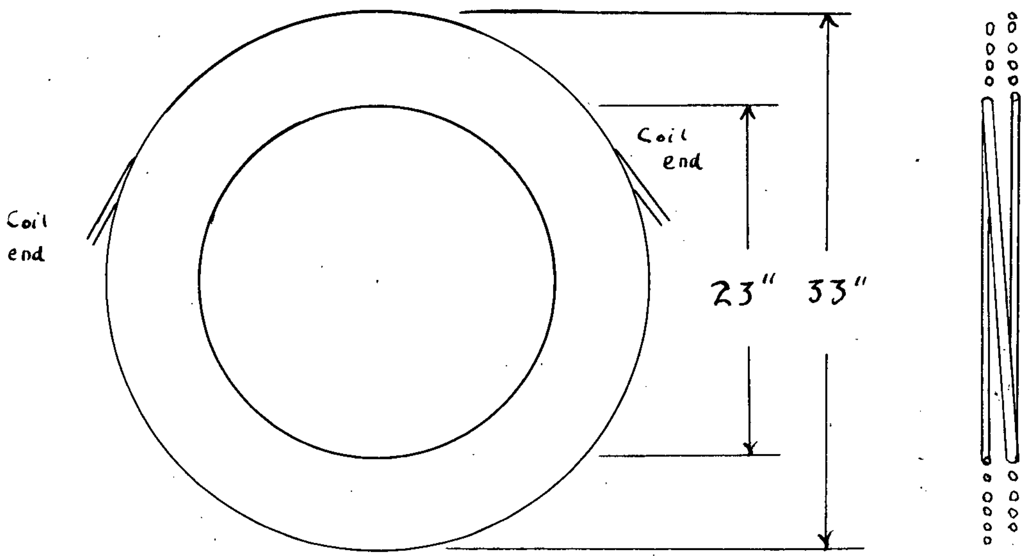

Fig. 2.

Double-pancake coil

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Chapter 1.

The Magnet

(a) Function of the magnet

The magnet was designed to bend a five mev. beam of protons and deuterons through a 90 degree angle for energy resolution.

(b) Pole Shape

Its general shape is shown in fig. 1. Various possible pole piece shapes were considered for this purpose but it seemed very desirable to be able to bend the ion beam to the left or to the right without shifting the magnet so that two experiments might be set up together. Consequently the other most considered design, that of a single quarter circle pole piece with banana coils wound round the poles with the whole magnet on a swivel, was given up. After examining possible shapes of pole taper needed to give the field actually required at the gap, and a round yoke on which to wind the poles, a square pole tip was chosen. This gave a very conventional design which is easily adapted for other experiments requiring a large $H\rho$ such as spectrograph applications or even for a cloud chamber; and provision was therefore made for altering the gap width and pole shape.

(c) Size

Consider an ion of charge e, mass m, moving with velocity v, entering a magnetic field of strength H. It will be bent in an arc of radius ρ such that

$$H e v = \frac{m v^2}{\rho}$$

$$H \rho = \frac{m v}{e}$$

In a consistent set of units, c. g. s., e. m. u.; with H in e. m. u. and e in e. s. u. we have, where c is the velocity of light,

$$H \rho = \frac{m v c}{e}$$

If the ion attained the velocity v by being accelerated through an electric field of strength E, then,

$$1/2 \, m c v^2 = e E$$

$$v = \sqrt{\frac{2e}{m c} E}$$

$$\text{therefore } H \rho = \sqrt{\frac{2 m c}{e} E}$$

The value of $H \rho$ required to deflect ions accelerated through an electric field of five million volts is[4] :

for protons, 3.22×10^5 gauss cm.

for deuterons $\sqrt{2} \times 3.22 \times 10^5 = 4.55 \times 10^5$ gauss cm., and
for tritons $\sqrt{3} \times 3.22 \times 10^5 = 5.6 \times 10^5$ gauss cm.

Protons could be deflected in both direction with a field of: $\frac{3.22 \times 10^5}{20} = 16{,}100$ gauss in a radius of 20 cms.. Deuterons in one direction with a field of :

$\frac{4.55 \times 10^5}{30} = 15{,}200$ gauss in a radius of 30 cms.. Tritons in one direction only with a field of:

$\frac{5.6 \times 10^5}{35} = 16{,}000$ gauss in a radius of 35 cm.. Therefore, a square pole tip of size 16 inches on a side, equal to 40.6 cm. on a side was decided on. This then set the size of the round pole pieces and thus the yoke cross section.

(d) Stability

Since this molecular beam would be required for the Van de Graaff electrostatic generator stabilization[5], and also for energy resolution of three kev. in five mev., we must require the $\frac{\Delta H}{H}$ to be equal to three parts in 10,000; as from (2) $\rho \Delta H = \sqrt{\frac{2mc}{e}}$ 1/2 $\frac{E}{\sqrt{E}}$

$$\text{and} \quad \frac{\Delta H}{H} = 1/2 \frac{\Delta E}{E}$$

When current stabilization is used $\frac{\Delta I}{I}$ must be less than $\frac{\Delta H}{H}$ because of the following factors, all of the order of a few parts in 10^5 or less

1. The width of the air gap varies due to the thermal expansion of the iron and the magnetic force bending the iron.

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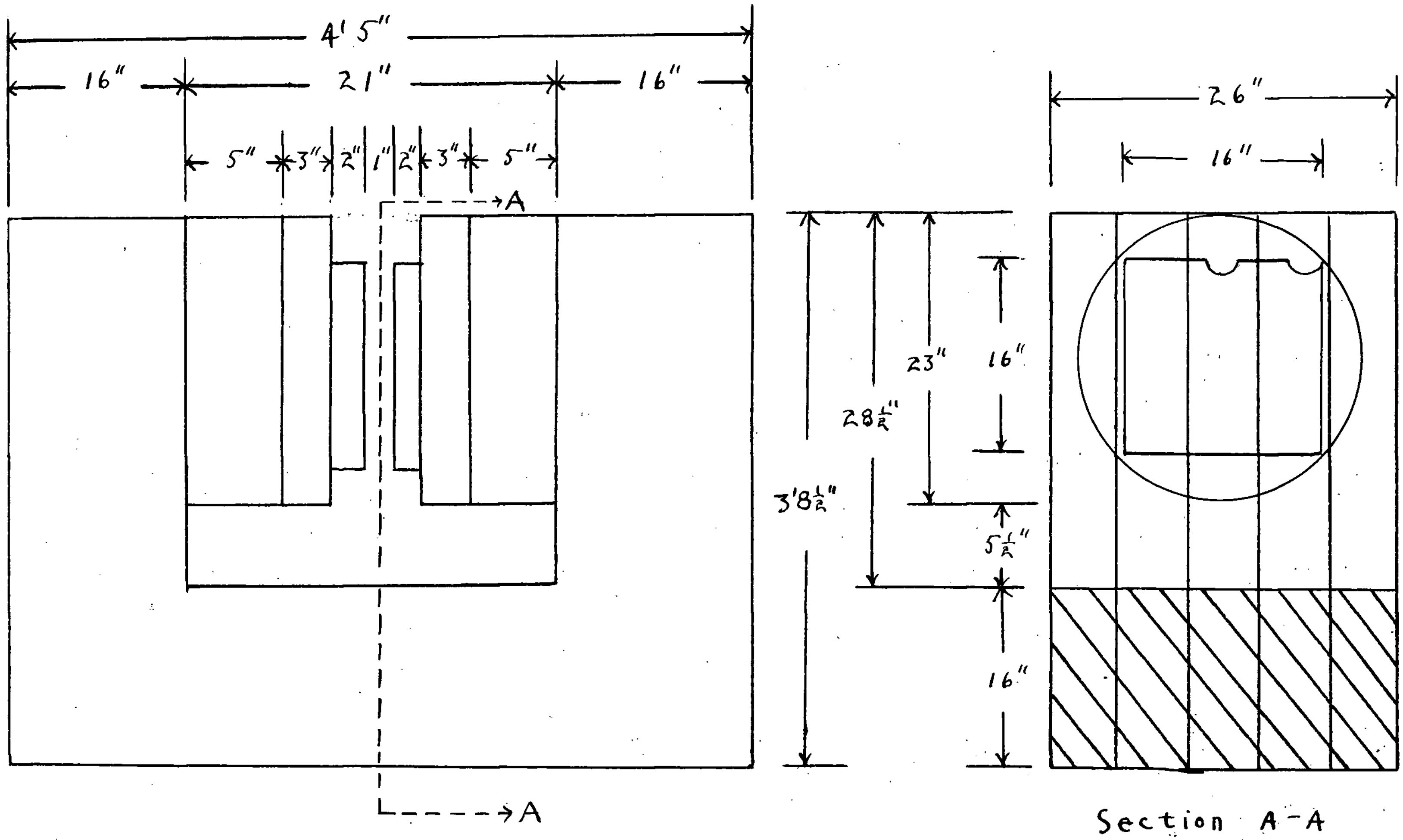

Magnet yoke and pole pieces

Fig. 3.

2. The incremental permeability of the iron and hysteresis vary with the previous magnetic history.[6]

3. There is a small mechanical hysteresis in the iron of the pole pieces, bolts and nuts.

(e) <u>Design of Magnet</u>

The design of the magnet and coils followed in this manner:

Take $H\rho$ as 6×10^5 gauss cm. and consider a maximum H of 15,000 gauss across a one inch gap, allowing a beam size of one half inch.

The pole tips, to be square, will be about 40 cm. on a side or 16 inches square; therefore the pole tip area is 256 square inches.

Assume a leakage coefficient of 1.8 =

$$\frac{\text{Total lines of force from pole to pole}}{\text{H at centre of gap x pole tip area}}$$

Now choose the round diameter of $16\sqrt{2} = 23$ inches giving an area of the round poles of

$$\frac{\pi D^2}{4} = 415 \text{ square inches}$$

With this and the leakage coefficient, the intensity in the iron of the round poles increases to:

$$\frac{1.8 \times 15{,}000 \times 256}{(11.5)^2} = 16{,}650 \text{ gauss}$$

Consider the yoke area to be 16 x 26 = 416 square inches

Then the magnetomotive force required, assuming 80 oersteds per inch for 15,000 lines/ sq. cm. for a low carbon steel, and an iron path length of 123 inches, is equal to

$$H_{air}\, l_{air} + H_{iron}\, l_{iron}$$

$$= 15{,}000 \times 1 \times 2.54 + 80 \times 123 \times 2.54$$

$$= 38{,}100 + 25{,}000$$

$$= 63{,}100 \text{ ergs}$$

Therefore the total $\frac{4\pi N I}{10} = 63{,}100$

and the ampere turns required, $N I = \frac{63{,}100 \times 10}{4} = 50{,}300$ ampere turns

Considering a maximum current of 45 amperes, then the number of turns would be $N = \frac{50{,}300}{45} = 1118$ turns

Copper tubing, which could carry the water as well as the electric current, was preferred. The lower limit on the bore diameter of this tubing was set by its use as a water channel for cooling while the upper limit was set by its ability to bend, as well as having a suitable value of resistance for the turns required. After some trial and error calculations, the size of the copper tubing which could be reasonably easily wound in the pancake shape was decided upon as 3/16'' outer diameter, 1/8'' inner diameter.

Window area would allow an average coil diameter of 28 inches so that for two times 23 turns per section, the length of copper, per pancake would be

$$\frac{2 \times 23 \times \pi \times 28}{12} = 337.5 \text{ feet}$$

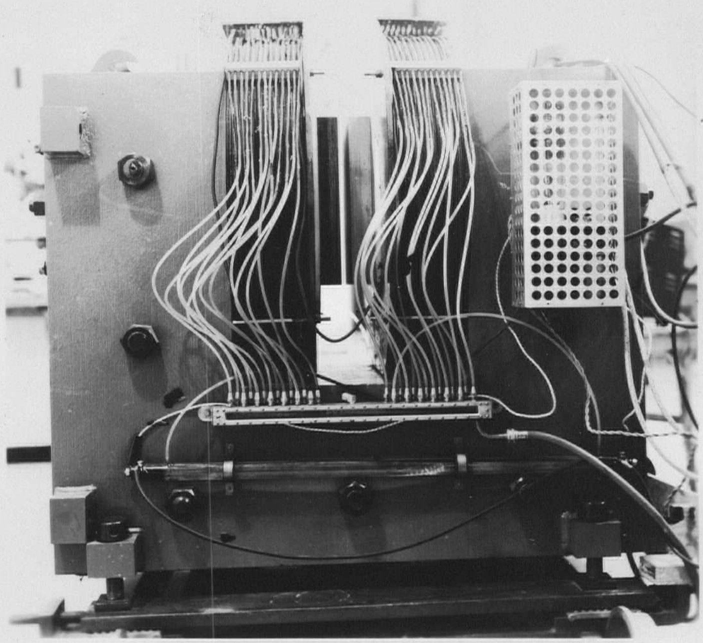

Fig. 4.

The Electromagnet

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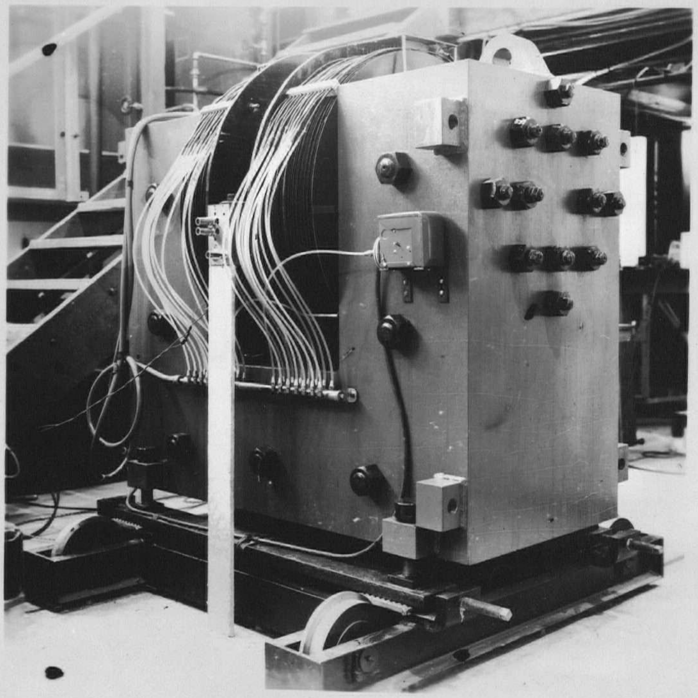

fig. 5

The Electromagnet

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For 24 coils in series the electrical resistance at 20 degrees C would be 4.48 ohms which at 50 degrees C would be increased to five ohms[1]. Thus a D. C. supply at 45 amperes, of voltage 5 x 45 = 225 volts would be required. The coils would have to dissipate, at this current, a maximum power of

$$I^2 R = 45^2 \times 5 = 10,120 \text{ watts}$$

(f) Particulars of magnet construction

The yoke and pole pieces were made of soft steel, the former of five U sections bolted together, the latter of four round and two square pieces bolted together. The specifications of the steel called for a carbon content of less than 0.1% and manganese content of less than 0.4% so that for a field strength of 15,000 gauss, the magneto-motive force required would be less than 80 ampere turns per inch.

The only well machined parts were the pole tips, pole pieces and the inside surfaces of the yoke to which the pole pieces were attached. These were machined to give the one inch air gap a tolerance of plus or minus 0.010 inches. This air gap could be increased an additional ten inches by removing the inner five inch sections of the pole pieces. The outside tolerance of the magnet was plus or minus 0.5 inches.

The square pole tips two inches by 16 inches square had two two inch diameter circular holes cut out as shown in figures 1 and 3, with like pieces of steel fitted for fine focussing of the beam. The cross section of the yoke was 16 inches x 26 inches which is sufficient to withstand an attractive force of 30 tons between the poles. The total weight of steel was 7.5 short tons.

The magnet is mounted on rollers on a steel trolley with roller bearing wheels running on steel tracks embedded in the floor under the Van de Graaff generator. In conjunction with the rollers four screws were provided at the base for horizontal positioning across the rail bed, while four more were provided for levelling (figures four and five).

(g) The magnet coils

The special design of the coils is illustrated in fig. 2 They were wound as double pancakes of two times 23 turns so that the ends came out tangentially on the outside. They were made of asbestos covered copper tubing, 3/16 of an inch outside diameter, 1/8 of an inch inside diameter so that the resistivity was less than 8 x 10^{-7} ohm-inches at 50 degrees centigrade. The inside diameter of the coils was 23 inches and outside diameter was 33 inches, making a total length of 338 feet. Each pancake was spaced by a 1/32 of an inch textolite insulating ring.

The individual coils were cemented together with glyptal before being baked with three coats of insulating varnish. Short copper strip join the coils in series electrically while two foot lengths of 1/4 inch saran tubing join them hydraulically in parallel to the cooling water manifolds.

(h) <u>The water cooling system</u>

At a pressure of 37 lbs./sq. in., 1.45 gallons of water per minute flowing through 26 coils in parallel kept the rise in water temperature to less than 25 degrees C at a current of 45 amperes. A pressure switch was incorporated in the intake manifold and connected into the interlock system. This prevented power being applied when no cooling water was in the coils. A lucite cover on the outlet manifold allowed observation of water flow through each coil.

The temperature rise was only ten degrees in a half hour at a current of 35 amperes when the water flow was stopped.

The maximum current flow for a 25 degree C temperature rise, when water cooled was in excess of 60 amperes showing that the design was quite conservative.

(i) The magnetic field

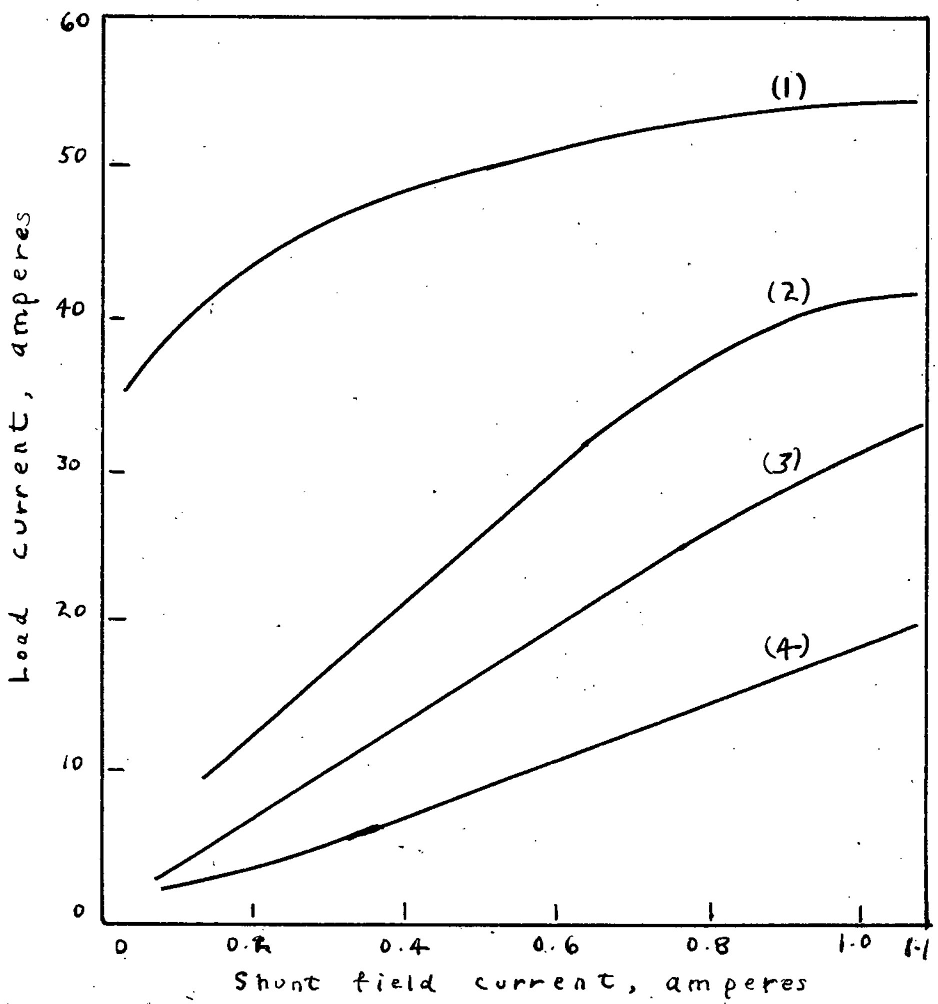
The maximum field measured in the gap at the centre at a current of 48.5 amperes was just over 19,900 gauss. The number of turns was 2 x 23 x 26 = 1,186 and therefore the N I was 57,500 ampere turns.

$$\text{Now} \quad \frac{4\pi N I}{10} = 19{,}900 \times 2.54 \quad X \times 123 \times 2.54$$

$$\text{therefore } X = \frac{72{,}200 - 50{,}500}{312}$$

$$= \frac{21{,}700}{312} = 69.5 \text{ ampere turns/ inch}$$

This confirms the design figure that the H is less than 80 ampere turns per inch. This point of 19,900 gauss was not the limit of magnetization but it was up on the knee of the magnetization curve (figure 12).



(1) Generator #1, no series field, 5 Kw. load

(2) " #2, " " " " " "

(3) " #1, series field in opposition, 5 Kw. load

(4) Generators #1 and #2 in series, series fields in opposition, 6 Kw. load.

Generators' Curves

Fig. 6

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Chapter 2.

The Power Supply for the Magnet Coils

(a) The generators

Two compound-wound D. C. generators were made available to supply the ten kilwatts of power for which the magnet coils were designed. One generator was rated at $5\frac{1}{2}$ kilowatts at 44 amperes while the other was rated at 6 kilowatts at 54 amperes. However, this total power was not available in the regulating system since the series field coils were connected in opposition to give a linear current-current characteristic to the machines when the shunt field coils were separately excited. This was more suitable for smooth control of constant sensitivity but caused a loss of 3.5 kilowatts in output power. Curves 3 and 4, figure 6 illustrate this effect.

Each generator was driven separately by a ten H. P. three phase A. C. motor using three V belts on multiple pulleys.

The two generators were connected in series to deliver up to 200 - 250 volts to the magnet coils. Their shunt field coils were also connected in series and supplied separately with up to one ampere of current by the control system.

Current Regulator Block Diagram

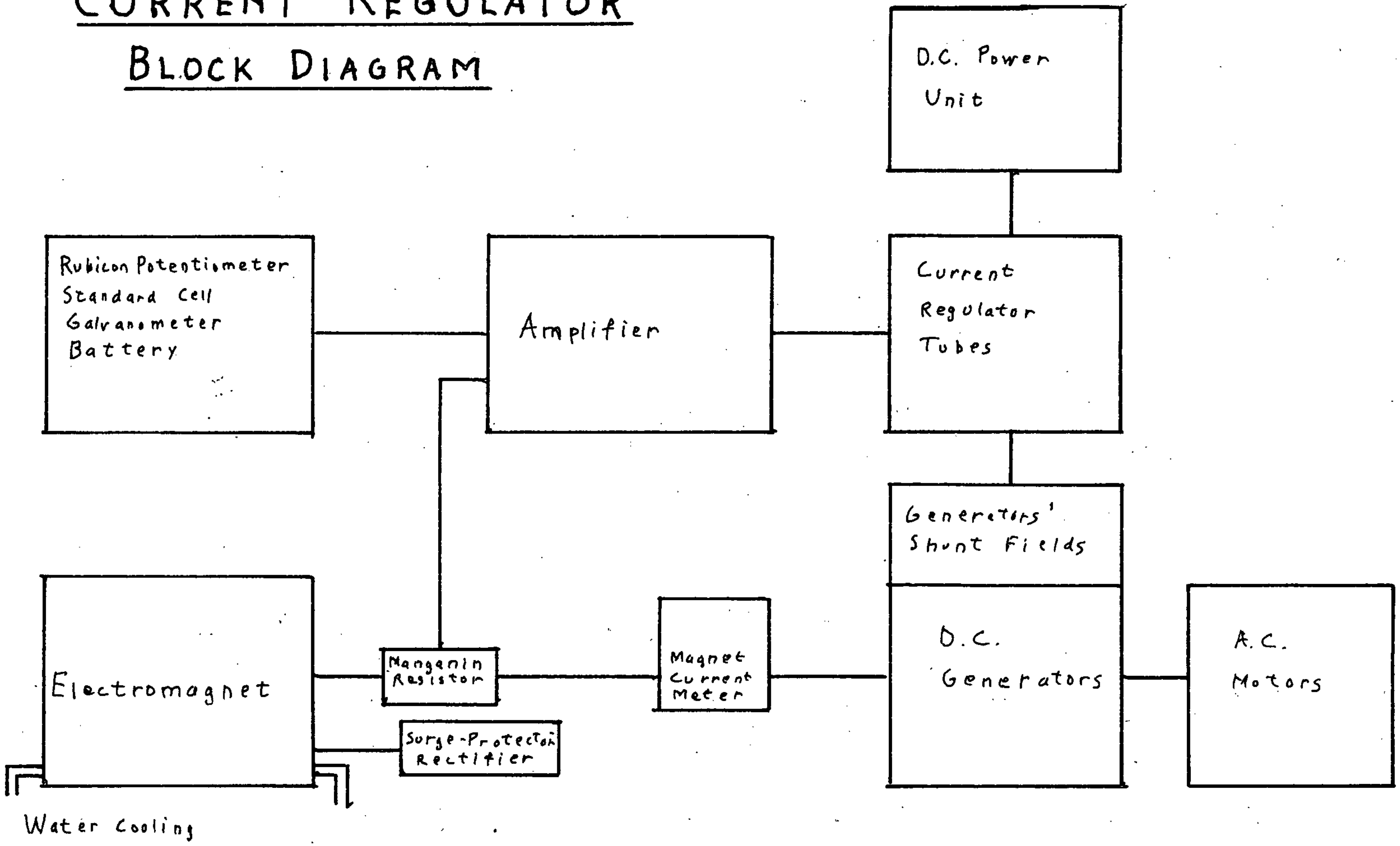

Fig. 7.

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Chapter 3.

The Regulating System

The objective of the regulating system was to give an easily varied but accurately regulated magnetic field. This has been achieved.

The type of regulator chosen using high vacuum tubes, was preferred over other types [7,8,9,10] because of its ease of operation and accuracy. The other most considered types were the saturable-core reactor [7] which had an accuracy of only one part in 1,000 and the photocell and galvanometer type [8]. The latter had adequate accuracy but required fine adjustment, more care and could lose control with large current changes.

A block diagram of the regulating system used here is shown in figure 7.

All switches and meters were mounted on one rack, the regulator rack, as part of the control console of the Van de Graaff generator. This also contained the Rubicon potentiometer, standard cell, galvanometer, batteries, amplifier, and the regulator tubes. At a distance from this of about 25 feet was the magnet itself with the manganin resister and surge-protector-rectifier. Lastly, the D. C. power unit, generators and motors were situated in a small adjoining room.

(a) Operation

The required magnet current was selected by the setting of the Rubicon potentiometer whose voltage'bucked' that developed across the manganin resistor inserted in the magnet current leads. The difference of these two voltage, 'the error signal', after amplification, was used to control the field current of the two generators through the regulator tubes. The magnet current faithfully followed any change in setting. Once the current was set, it remained constant throughout the warm-up period and throughout the days' variations in temperature.

(b) Precision of the System

The varations in magnet current are twofold:

1. Slow drift due to warming up of magnet, coils, generator and other components.

2. More rapid variations due to commutator ripple and other noise pick-up.

The precision of the current control depends on the following points:

1. The value of the manganin resistor must be such that the minimum variation that can be tolerated in the magnet current provides an error signal above the input noise level of amplifier.

2. The temperature variation in resistance in this resistor must be kept less than one part in 10,000.

3. The input noise level of the amplifier must be kept to a minimum.

4. An accurately controlled D. C. reference (or 'bucking') voltage must be available, whose variation is also less than one part in 10,000

5. Sufficient gain must be available in the amplifier and control loop to allow the system to follow up any variation on the input or output so the error current does not exceed 1/10,000 part of the current passing; however the system must not overshoot or hunt.

In order to regulate over the current range from five to 45 amperes, to one part in 10,000, and give a 25 μ volt error signal, a resistor of at least

$$R = \frac{25 \times 10^{-6}}{5 \times 10^{-4}} = 0.05 \text{ ohms is needed.}$$

The upper limit of the resistor is governed by the amount of heat it must dissipate at high currents. In this case, at 45 amperes, it must dissipate

$I^2 R = 101$ watts, which necessitates adequate cooling to keep its temperature and thus resistance constant.

By using manganin shunt strip of temperature coefficient $\alpha = 0.00002$ per degree centigrade, it is required that:

$$\frac{\Delta R}{R_o} < \frac{1}{10,000}$$

now $R = R_o (1 + \alpha t)$

therefore $\Delta R = R_o \alpha \Delta t$

and $\frac{\Delta R}{R_o} = \alpha \Delta t$

therefore $\alpha \Delta t < \frac{1}{10^4}$

$$\Delta t < \frac{10^{-4}}{2 \times 10^{-5}}$$

$$< 5 \text{ degrees C}$$

When the manganin resistor was made up and attached to the cooling water system it was found that over an eight hour period its temperature did not vary more than 0.2 degrees C. The above condition was therefore easily fulfilled.

Chapter 4.

The Units of the Regulator

(a) Standard Resistor

A 0.05 ohm water cooled manganin resistor was made up for the reasons given in chaper three above. A $3\frac{1}{2}$ foot length of one inch manganin 'shunt' was mounted in a glass tube and connected to the magnet water cooling system. Electrical connections were made through heavy brass cylinders having separate potential and current terminals. These cylinders were soldered to the ends of the manganin strip. After annealing, the complete resistor was sealed into the glass tube and mounted on the magnet frame as shown at the bottom of figure 4.

Care was taken to have identical shielded copper leads both from this resistor and from the reference voltage source leading to the amplifier input.

The temperature variation in the resistor throughout one day, at currents up to 15 amperes was negligible. Temperature of the cooling water available was found to vary from day to day by a degree or two but remained constant throughout the day, to much less than one degree centigrade as checked over a two week period.

(b) Standard reference voltage

The standard reference voltage was obtained from a modified Rubicon type B potentiometer, with its associated standard cell, galvanometer and battery supply. The modification consisted in bringing out an extra terminal so that on the most used range, an uninterrupted voltage was available while the potentiometer was being checked for calibration. The voltage range of the potentiometer had also been extended to 6.4 volts so as to handle currents in this regulating system up to 128 amperes if that ever became necessary.

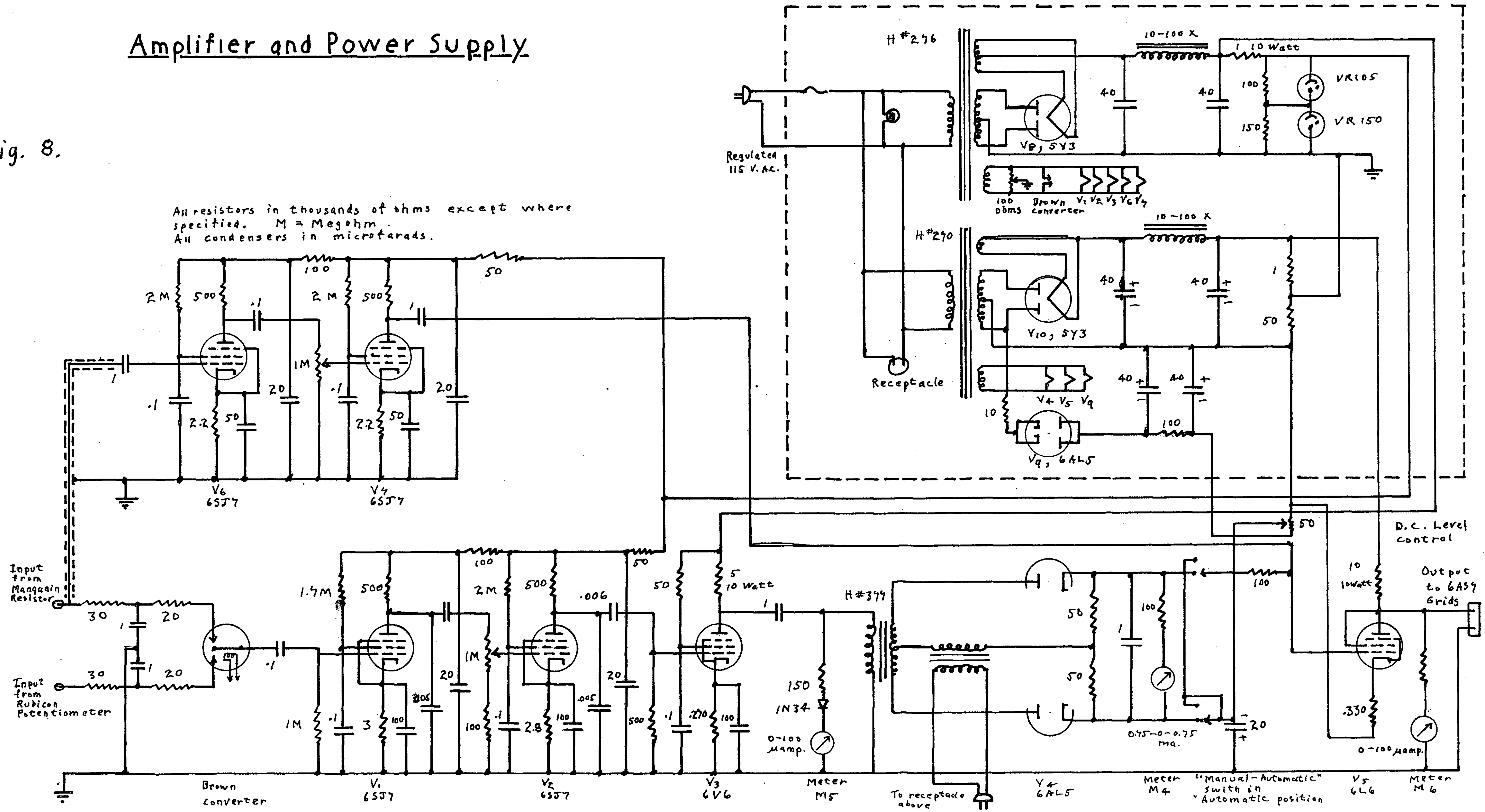
The standard cell was certified accurate to one part in 100,000 at room temperature and the potentiometer to about two parts in 100,000[12]. The determining accuracy was therefore the constancy of voltage of the battery supplying the potentiometer. After trying various sources of dry cells and storage batteries, two heavy duty Exide lead and sulfuric acid batteries were chosen for the final tests. On the 50 ma. drain required, they dropped in voltage about 0.5 μ volts per minute after being connected continuously for 13 days. Superimposed on this, however were small temperature fluctuations.

Primary cells of zinc and carbon in NaOH appeared to be

Amplifier and Power Supply

Fig. 8.

All resistors in thousands of ohms except where specified. M = Megohm.
All condensers in microfarads.



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the only ones having the necessary stability and low temperature and voltage drift on low current drain[13,14]. A number of cells of this type, Ferbatco F B 4 had been ordered from Ferguson Battery Company, Slough, England, but have not yet been delivered.

(c) Brown Converter and amplifier

A Brown Converter vibrator[15,16,17] followed by a conventional three stage R-C coupled amplifier, feeding a lock-in detector provided the D. C. amplification with high gain and stability required to follow the slow drifts in current. An additional two stage A. C. amplifier was added in parallel to look after more rapid variations in current. Both of these were then fed into one direct-coupled stage which was then directly coupled to the regulator tubes. Available voltage gain, at 60 cycles, in the three stage A. C. section was over 300,000 and in the two stage A. C. section, 5,000 (at 1,000 cycles per second). The power supply for the whole amplifier was built on a separate chassis to keep the power line frequency out of the system. The circuit diagram for the above is shown in figure 8 and follows that used at Chalk River[18].

A 400 cycle Brown Converter had been decided upon for reasons of lower noise, less phase delay and greater efficiency. The noise of the 60 cycle type is about two μ volts due to the capacitive coupling of the contacts on the vibrating reed to

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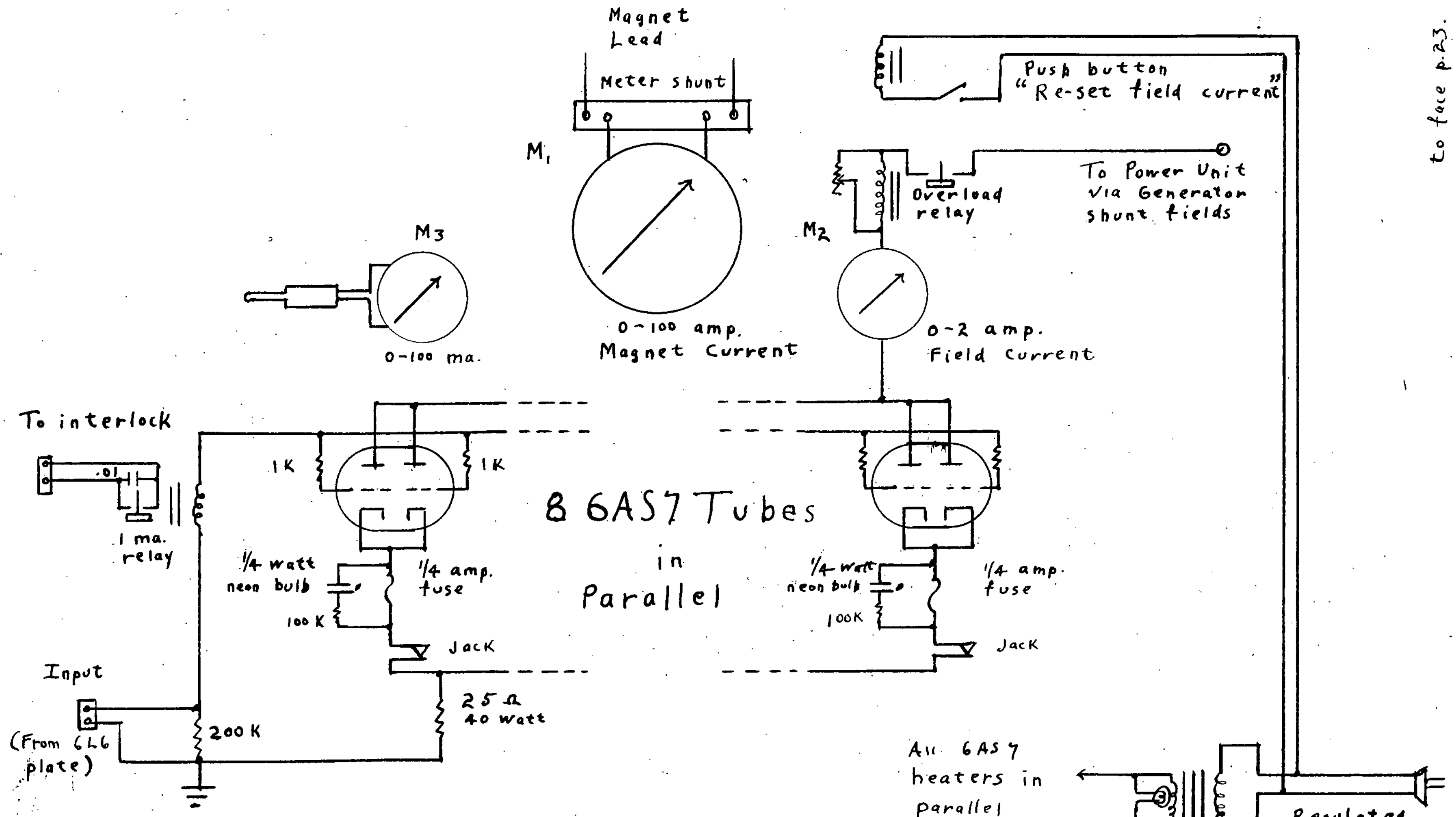


Fig. 9.

Regulator Tube Chassis

the exciting coil[15,16,17]. In the 400 cycle one, the exciting coil leads are isolated and brought out at the side through a shielded cable connector to reduce this type of coupling. The phase shift in the amplifier is considerably less at 400 cycles than at 60 cycles. Lastly, the greater efficiency is due to the fact that information on voltage or current fluctuation is gathered 400 times a second instead of only 60 times a second. As the 400 cycle vibrator did not arrive until recently, all tests have been carried out with the 60 cycle one.

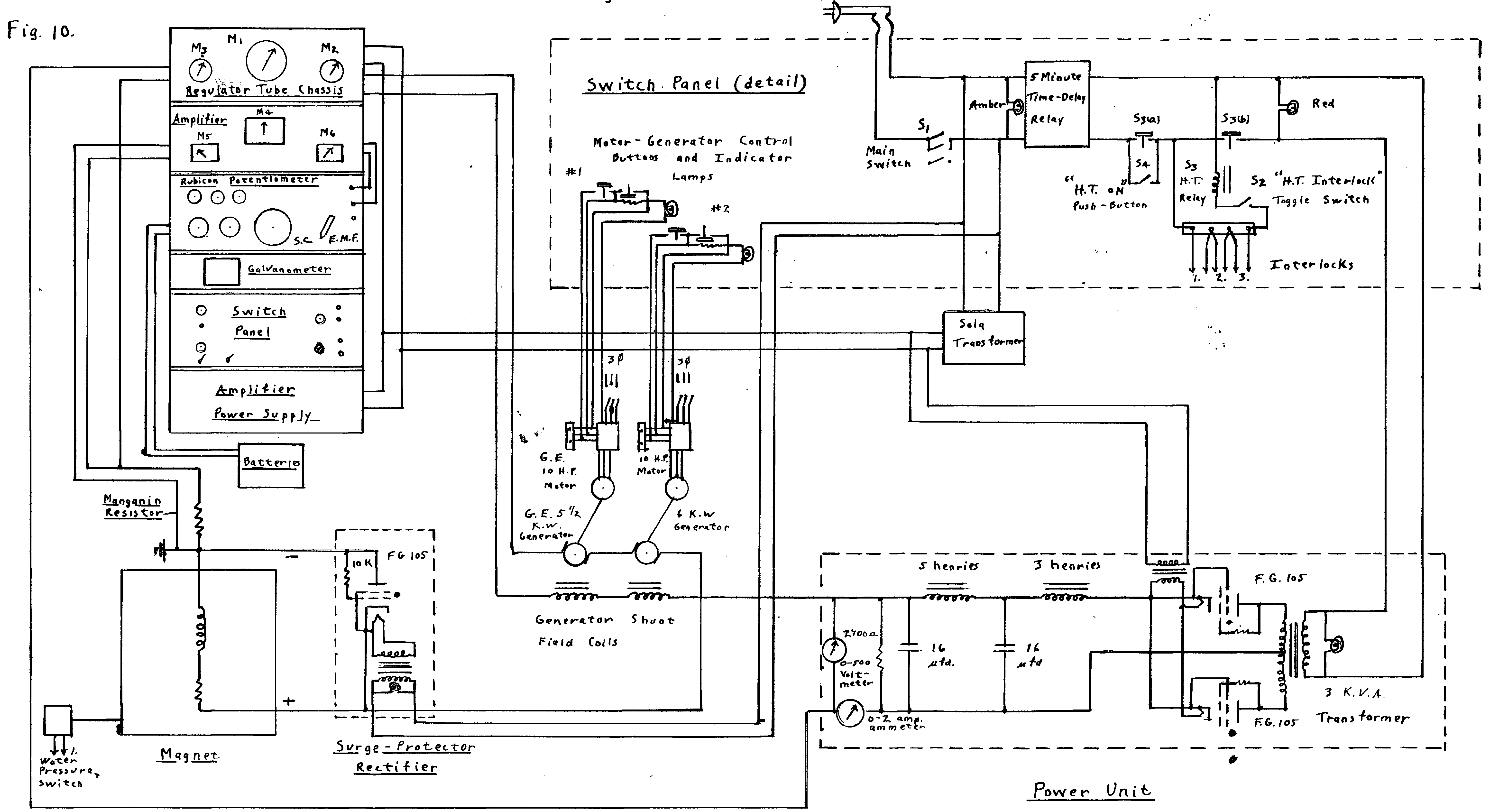
(d) Current regulating tubes

Eight 6 A S 7 tubes in parallel connected in series with the generator fields provided the control of the magnet current. These were mounted on separate chassis together with a filament supply transformer and associated devices as shown in figure 9. At low current, the individual tube's internal resistance varied by as much as 100% but became equalized as the current increased. For longest life, the tubes passed only half rated current with full load on the generators.

Complete check on the operation of each tube was provided by a circuit opening jack as well as a 'slo-blo' fuse and neon bulb. Cathode current of each tube was read by a milliammeter and jack plug. The fuses, rated at $\frac{1}{4}$

Current Regulator; Wiring and Power Unit

Fig. 10.



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ampere protected the circuit against shorted tubes which would then be pointed out by a glowing neon bulb. An open circuited tube could be found by checking for cathode current. In addition to the above, a current overload relay, adjustable from 0.65 amperes to 2 amperes, was inserted in the common plate lead of the tubes. Lastly, a one milliampere relay, connected to the interlock system, was inserted in the control grid circuit to prevent the grids from going positive.

The 1,000 ohm resistor in each grid lead was a 'grid stopper' to damp out any parasitic oscillations. Finally, a small amount of negative feedback as well as bias was provided by a 25 ohm power resistor in the common cathode lead.

(e) <u>Power Unit</u>

A 400 volt, one ampere power supply fed the 6 A S 7 tubes and generator fields in series. This unit, shown in figure 10 used two G. E. F G 105 thyratrons in a full wave circuit with choke input, followed by an additional L C filter section. The ripple is less than 0.2 %. The H. T. (plate) transformer was a three K. V. A. oil filled power-line transformer with its two 1040 volt windings in series as centre-tapped secondary and its two 104 volt windings also connected in series for the primary.

(f) Protective devices

The complete system (figure 10) was protected by three interlocks and an overload relay, as well as the surge-protector-rectifier across the magnet coils themselves. H. T. of the power unit was shut off if the cooling-water pressure failed, if the regulator tubes drew grid current, or if the power unit cabinet doors were opened. The current overload relay in the generators' field circuit as mentioned above and shown in figure 9, would also interrupt power to the magnet in case of short circuit. Lastly, a surge-protector thyratron rectifier, mounted at the magnet, was connected in reverse polarity across the coils to discharge them quickly. This rectifier, an F G 105, could pass a surge current of 200 amperes at 1,000 volts. The surge that could be expected as calculated from a 5 ohm resistance of F G 105 is not greater than 225 volts. The filament of this thyratron was connected in the system such that it had to be on and warmed up before power could be supplied to the magnet. This is described in the next chapter.

Chapter 5.

Operation of the control system

(a) General switching

The switching arrangement of all the units is shown in figure 10. One toggle switch and one push button turn on all the electronic equipment while an additional push button is needed for each motor generator. (These may be controlled together if desired with a small change in wiring, by one set of push buttons.) The main toggle switch S_1 turns power on to all the thyratron heaters and Sola constant voltage transformer as well as a five minute time-delay-relay. The complete amplifier and all heaters but the surge-protector-rectifier are fed from the Sola transformer. The time-delay-relay allows the thyratron heaters to warm up before H. T. can be applied to the power unit. Thus, after five minutes, provided all interlock switches are closed, field excitation is applied to the generators by pressing push button S_4. This closes relay S_3 which applies power to the plate transformer of the power unit. H. T. can be interrupted manually without re-introducing the time-delay, by means of toggle switch S_2. All the equipment but the motor generators is switched off by switch S_1.

(b) The motor generators

The two motors are controlled individually by on-off push buttons which are provided with indicator lamps. The lamps and buttons are mounted on the switch panel. The motors may also be controlled independently by push buttons in the motor-generator room.

(c) The Rubicon potentiometer

The Rubicon potentiometer, used as the primary control of the system, requires no extra switching in checking its calibration when used on the main 1.6 volt range. By this means, the accuracy of the current setting may be kept as high as possible inspite of any variations in the potentiometer battery supply, for magnet currents up to 32 amperes.

For very small currents, or for currents above 32 amperes, calling for the use of the 0.16 or 6.4 volt ranges, the control loop of the regulator system has to be opened temporarily and the magnet current left partially unstabilized during the re-calibration of the potentiometer. This is done by first switching the 'manual-automatic'

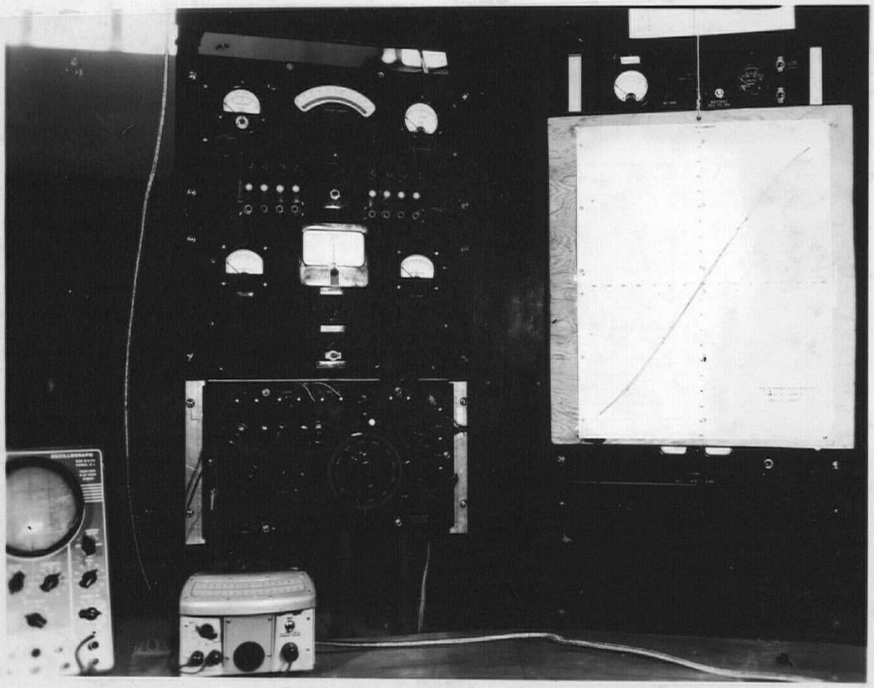

fig. 11.

The Control Panel

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switch on the amplifier to 'manual'. Calibration or re-checking of the calibration is then carried out by turning the E. M. F. - S. C. switch on the Rubicon potentiometer to S. C. (standard cell) position. The regulator system is returned to self-stabilization by reversing the above switching procedure.

(d) <u>Manual-automatic switch and D. C. level control</u>

The 'manual-automatic' switch cuts out the D. C. amplifier portion of the circuit but leaves the low gain A. C. loop still in the circuit. While in this 'manual' position, the magnet current may be altered over the complete range, by adjusting the 'D. C level' control knob on the amplifier.

(e) <u>Current and field setting of the magnet</u>

The magnetic field desired is obtained by referring to the large graph of the hysteresis loop mounted at the control panel, as shown in figure 11. The magnet current is then set to the indicated value by turning to the appropriate setting on the Rubicon potentiometer. The actual magnet current is indicated by the large meter M_1 on the regulator tube chassis as shown in figure 10. For example, with the 0.05 ohm manganin resistor, a current of 20 amperes was chosen by setting the Rubicon potentiometer to 1.0000 volts, and then adjusting the D. C. level control knob to make the balance meter M_4 read at centre. This gave a magnet field strength of 11,400 gauss.

The additional meters on the control panel tell precisely what is happening to the system. An understanding of their function and operation aids in tracing any faults in the system. Ammeter M_2 reads the generators' shunt field current and should read between 0 and 1 ampere in direct proportion to the magnet current. The terminals of the milliammeter M_3 come out from the front of the panel to a jack plug which may be inserted in the cathode circuit of each 6 A S 7 tube to check its operation. Ammeter M_1 as mentioned in the preceding paragraph reads the magnet current directly and must follow the voltage setting of the Rubicon potentiometer directly.

The other three meters, on the amplifier chassis panel, tell the operation of the rest of the electronics of the system. Voltmeter M_4 when reading centre, indicates that the current setting agrees exactly with the desired value as chosen by the Rubicon potentiometer setting. A. C. voltmeter M_5 reads the magnitude of the error signal being transmitted by the amplifier. For best operation under normal conditions, this should read as close to zero as possible. This may be always kept reading zero for all magnet current settings by re-adjusting the D. C. level control knob, which will maintain the balance meter M_4 at centre as well. Correct setting of the current will not be obtained unless balance meter M_4 is set at centre. Voltmeter M_6 reads the D. C. voltage applied to the grids of the 6 A S 7 regulator tubes. Meter M_4 and M_5 together give the phase and magnitude respectively of the error signal in the system at any time.

Initial setting up of the regulating system and additional adjustments are discussed in appendix 3.

Chapter 6.

Experimental Results

(a) Drift of the magnet current and magnetic field

Slow drifts of the magnet current were satisfactorily small, of the order of a few parts in 10,000 over a few minutes and up to seven hours as taken from field measurements using flip-coils and a fluxmeter(appendix 4). By using the highly accurate proton resonance method [19, 20, 21, 22, 23], slow drifts of the field were then measured to be one part in 10,000 over an eight minute period, increasing to only three parts in 10,000 over the long period of seven hours. Part but not all of this can be accounted for by thermal contraction of the iron decreasing the width of the air gap as discussed in appendix 2. The rest can more than be accounted for by a decrease of nearly two per cent in the resistance of the magnet coils for the five degree temperature drop at the current used for this test. This could justify the above mentioned accuracy of the current drift in the regulator since on the other hand, the generator coils would have heated up about 25 degrees C at the same time. The corrected drift, nevertheless, was a small but a definite increase in magnetic field.

A small amount of commutator ripple was observed but was reduced satisfactorily after large condensers were connected across the generator brushes.

(b) Amplifier and regulating system

The Brown converter and the amplifier and lock-in detector provided D. C. amplification with a minimum inherent drift. This resulted in almost complete compensation for the thermal effects in the components of the regulating system. The few parts in ten thousand drift observed, after correction for battery drift and proton head oscillation drift are very insignificant compared to the one to two per cent or greater changes in resistance of the magnet and generator coils due to cooling or warming.

The gain and stability of the system was investigated by trying different values for the manganin standard resistor. With 0.05 ohms, the D. C. amplifier voltage gain could be advanced to 600 before low frequency oscillation or 'hunting' of the system set in. This showed up on all the meters and in the magnet field as shown on the proton resonance 'scope. Various other values of resistance down to 0.0005 ohms were tried allowing the gain of the amplifier to be increased to about 30,000, but with the stability of the system decreasing to only a few parts in 1,000 over short periods. With the lowest value of resistance the noise in the input to the amplifier was as large as the error voltage. Part of this noise was 60 cycle hum due to the 60 cycle Brown converter[15,16,17]. The rest of this was due to the first tube circuit, most probably from the heater.

The 400 cycle Brown converter with a separate supply of 400 cycle power feeding it and the lock-in detector would allow use of a smaller manganin resistor or response to a smaller error voltage. A stabilized 400 cycle oscillator and power amplifier was built and tested but has not yet been incorporated into the system.

Best stability and accuracy was obtained using the 0.05 manganin resistor. Repeatability of the current setting and the field was good and overshoot on application of a step voltage to the input was small. Repeatability of the field over a five day period as measured with a flip-coil and fluxmeter was within ½%. Momentary overshoot of the current on application of a step-voltage was ¼ ampere in 20 amperes, about 1%. This overshoot was not a continuous error, but this overshoot did increase in value if the voltage gain of the amplifier was decreased below a few hundred.

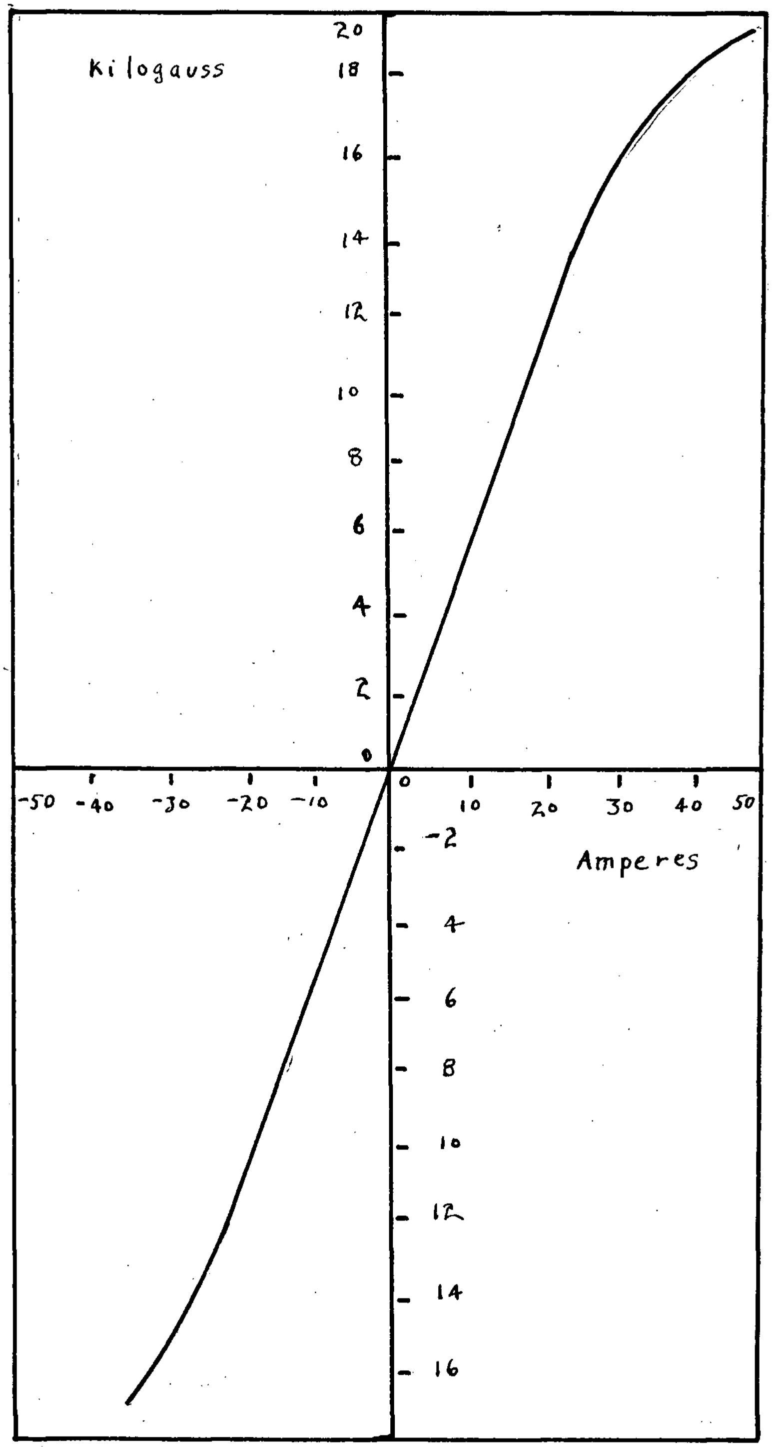

Fig. 12.

Hysteresis Loop and

Magnetization Curve

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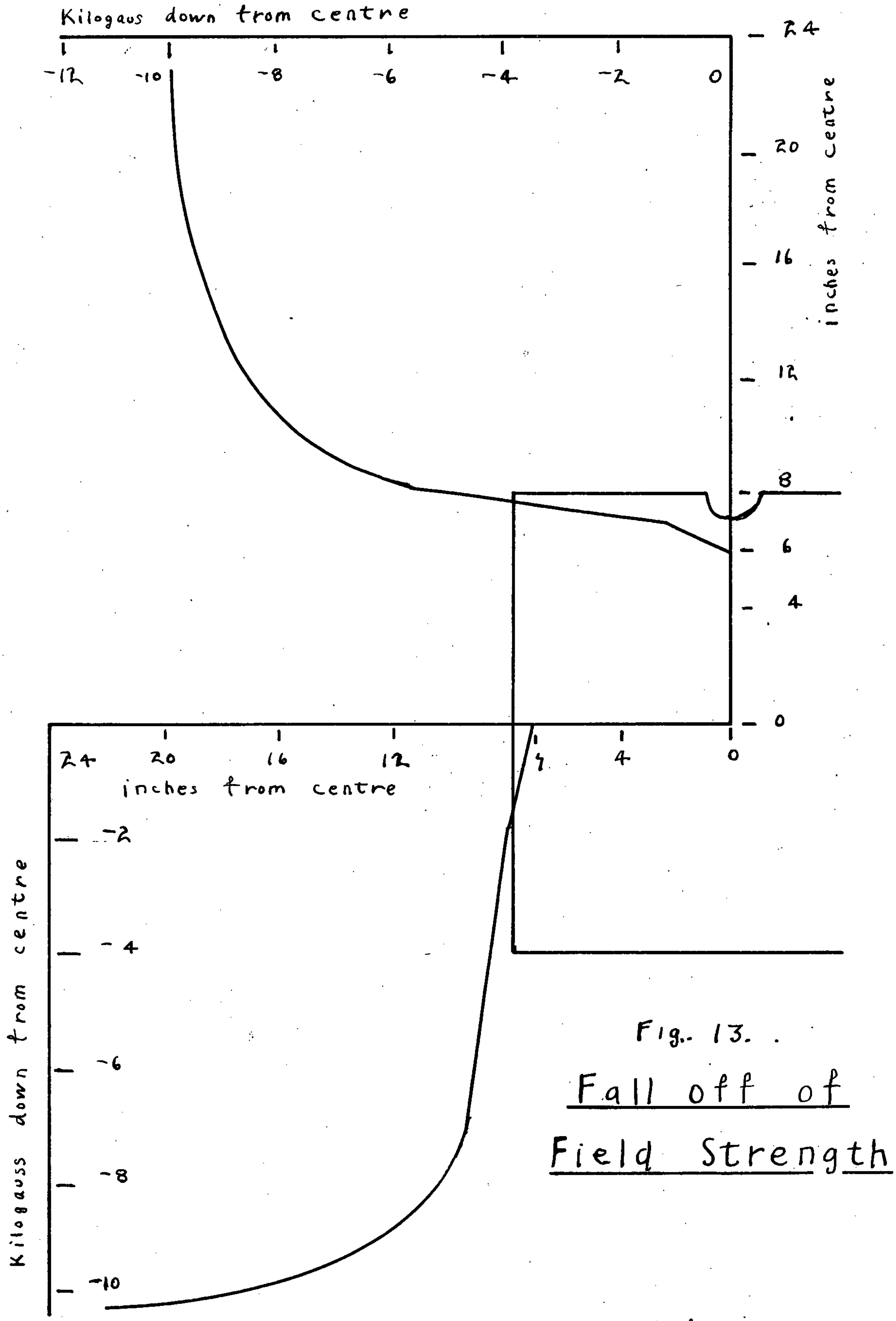

Fig. 13.

Fall off of Field Strength

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The time constant of the system in response to a step-voltage was between one and two seconds, which was roughly the time constant of the generators, but less than that of the magnet. This was measured independently to be close to three seconds using a storage battery, meter and stop-watch. It was the time taken for the current to rise to 63% of its final value and to fall to 37% of its initial value.

(c) Performance of the magnet

The inductance of the magnet was 13.9 henries as measured from its time constant of 3.02 seconds. The resistance of the coils at 20 degrees centigrade was 4.6 ohms. At a current of 48.5 amperes it gave a field strength of 19,919 gauss as measured with a flip-coil and fluxmeter. The saturation curve has its knee at 18,000 gauss while the hysteresis loop is only 0.2 amperes wide at a current of 15 amperes. These are superimposed in figure 12. The retentivity, of the order of 70 to 100 gauss, was surprisingly small. Figure 13 shows the fall off of field in the horizontal and vertical directions. This shows that the leakage flux is small which confirms the design described in chapter 1.

From the calculations given in chapter 1 under 'The magnetic field' it appeared that the H required for a field of nearly 20,000 gauss at the centre was about 70 ampere-turns per inch, 12 % better than was expected.

The temperature rise of the coils at 60 amperes was far less than anticipated, only 25 degrees centigrade. This was mostly due to the fact that the water pressure available in the basement of the Physics building where the magnet is located has been high, from 35 pounds to 40 pounds per square inch as against the 25 pounds per square inch assumed in the design. The magnet, containing seven and one half tons of iron and over 500 lbs. of copper, has a large thermal time constant such that at medium currents, up to 12 amperes the cooling was sufficient not only to keep the temperature rise down but to bring the magnet temperature gradually down from that of the room to the temperature of the cooling water, some five to seven degrees centigrade lower. From calculations based on 50 % effectiveness of iron in absorbing heat, it would take about two hours for the temperature of the iron to drop one degree centigrade at a current of 12 amperes, and water pressure of 37 pounds per square inch. (appendix 2)

(d) <u>Proton resonance measurement of field drift</u>

An R. F. head of a proton resonance magnetometer of design following that of T. Collins was built up to measure the magnetic field drift[24]. It was inserted in the one inch air gap of the magnet as shown in figure 5 so that although the search coil was in a homogeneous part of the field the electron tubes were as far out of the magnetic field as possible. A sensitive short wave receiver together with a General Radio heterodyne frequency meter, an amplifier and an oscilloscope were used in conjunction with this head to carry out the measurements of field drift. The measurements taken over a one day period are given in appendix 1.

The measurements of drift were taken in the following manner. The magnetic field was set with the current regulator to a value within the range of the oscillator for a proton sample in the search coil. The frequency of the R. F. head oscillator was adjusted till the proton resonance signal after amplification was observed near the centre of the trace on the cathode ray oscilloscope. The oscillograph trace was then calibrated in gauss as described in appendix 1. By tuning the short wave receiver and heterodyne frequency meter to the R. F. frequency, it could be measured to one part in 10^5 by listening for the zero beat. Readings of the oscillator frequency, heterodyne meter crystal calibration as well as the drift in the batteries supplying the Rubicon potentiometer were taken during the day and were used in correcting the drift observed in the motion of the proton resonance signal across the oscilloscope

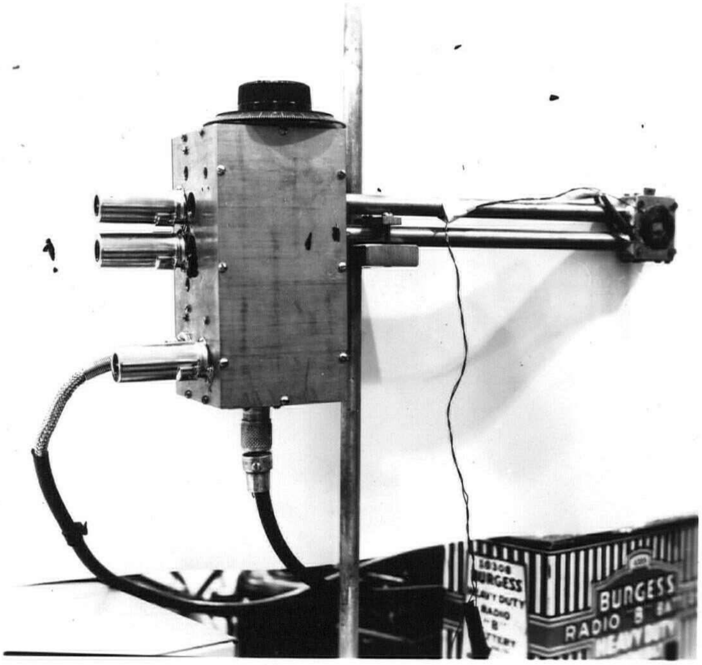

fig. 15.

Proton Resonance R. F. Head.

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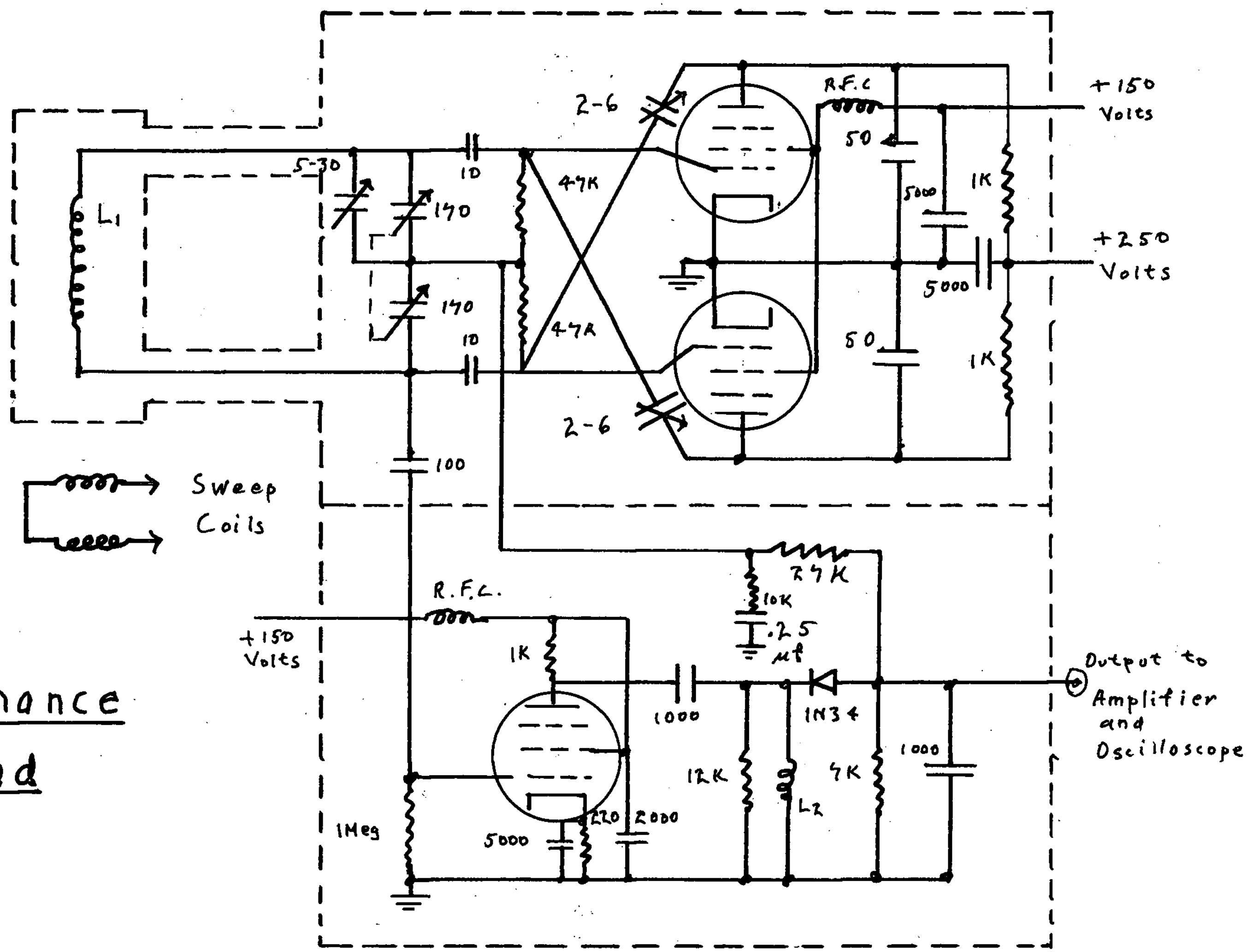

All tubes 6AG5; All condensers in μμf.
20-42 Mc/s – L_1 = 8 turns

Proton Resonance
R. F. Head

Fig. 14.

to face p. 37.

screen.

(e) Proton resonance R. F. head

The circuit diagram, fiqure 14, shows the head to contain a 'weakly oscillating detector' consisting of a pair of 6 A G 5 tubes in push-pull arrangement. The oscillations are kept small by feedback from the additional 6 A G 5 tube connected up as a low gain amplifier[24]. Only one control, the two-gang variable air condenser, is needed to change the frequency to any value in the range from 20 to 42 megacycles per second. This condenser together with the search coil inside of which is placed a 0.1 molar solution of $MnSO_4$, forms the tank circuit which is loosely coupled to the oscillator tubes.

The complete R. F. head is rigidly mounted in a heavy brass box with the search coil protruding as illustrated in figure 15. Two 40 turn double pancake wound sweep coils are cemented to the outside shield plates of the search coil for 'wobbling' the field.

(f) Simple proton resonance theory

Protons, of spin $I = \frac{1}{2}$, when in a constant magnetic field H_o will orient themselves in one of the two quantized energy states; the spin can be parallel or antiparallel to the field. If a sample of protons is placed in a coil between the poles of an electromagnet with the axis of the coil at right angle to the poles, then transitions between the two states will be induced when the frequency of the signal applied to the coil satisfies the resonance condition[25]

$$2\pi\nu = |\gamma| H_0 \quad \text{where}$$

$\gamma = \frac{u}{\hbar I}$ is the ratio of the magnetic moment to the angular momentum of the nucleus,

ν is the frequency in cycles per second

and H_0 is the magnetic field intensity in gauss at the nucleus.

By using the most recent value of γ and substituting in the above equations, the simple relation is obtained for the magnetic field H_0 in terms of the frequency[24,25].

$$H_0(\text{kilogauss}) = 0.2348\ (\pm\ 0.0002)\ f(\text{in mc/s})$$

The accuracy of this equation is limited by that in the known value of γ[26].

(g) <u>Future use of proton resonance for stabilization</u>

Although up to the present the proton resonance signal has been used only to measure the field, it is intended to feed this information derived from the magnetic field directly into the current regulator so as to keep the field constant and stabilized against all changes[25]. The above type of R. F. head is very suitable for this when followed by a discriminator or lock-in detector, for it has a large signal to noise ratio, better than ten to one, and has only one main frequency control.

Three or four R. F. heads may be necessary to cover the range of fields from a few kilogauss to 20 kilogauss as indicated in the table below:

frequency of oscillator mc/s	H kilogauss
8.52	2
17.04	4
42.6	10
85.2	20

The lower limit of field measurements using this method is set by the weakness of proton signals below about 3,000 gauss[27], while the upper limit is determined by the design of a stable variable high frequency oscillator with a separate tank coil, tunable up to 85 mc/s.

Appendix 1.

Measurement of field drift using the proton resonance method.

(a) Calibration of the oscilloscope

The oscilloscope X plates were fed from the same source which provided the 'wobbling' current for th sweep coils around the search coil so that two resonance peaks were observed each cycle. The oscillator dial was moved up and down and the frequency for which the resonance peaks were at the extreme right and extreme left of the screen noted. From this and the relation given in chapter 6, the trace of the scope was calibrated in gauss.

The results are summarized as follows:

Oscillator dial reading	Heterodyne meter frequency mc/s	Crystal check correction mc/s	Corrected frequency mc per s
74.8	14.9395	-0.044	2 x 14.8955 = 29.791
74.6	14.8430	-0.044	2 x 14.7990 = 29.598

The factor two came in as the second harmonic of the hetero-dyne frequency meter was used. Therefore the width, represented by the four inches of oscilloscope trace

$$= 234.8 \times (29.7910 - 29.5980)$$

$= 234.8 \times 0.103$

$= 24.18$ gauss

and per 1/10 inch division

$$= \frac{24.18}{40} = 0.6046$$

$$= 0.60 \text{ gauss.}$$

(b) Short time test for eight minutes

The equipment had been running for five hours when this test was made. The battery drift was negligible. However the oscillator increased 0.0008 mc/s in frequency from the zeroth to the eighth minute which would show up as a drop in field of

$$234.8 \times 0.0008 = 0.188 \text{ gauss}$$

$$= 0.2 \text{ gauss}$$

the observed fluctuation was from $\frac{1}{2} \times 0.6 = 0.3$ gauss

to $-1 \times 0.6 = -0.6$ gauss

therefore correcting for the 0.2 gauss drop, the fluctuation in the field was from $+ 0.3$

to $- 0.4$ gauss for eight minutes

The average measured field over the eight minutes was

$$234.8 \times 29.65 = 6{,}962 \text{ gauss}$$

Therefore fluctuation was $\frac{.7}{6962}$ = 1 part in 10,000 of the field over a period of eight minutes.

The value of the manganin resistor used in the current regulating system was 0.0499 ohms. The voltage setting on the Rubicon potentiometer was 0.6006. Therefore, the magnet current was $I = \frac{0.6006}{0.0499} = 12.032$

$= 12.03$ amperes.

(c) <u>Seven hour test</u>

The small voltage dial on the Rubicon potentiometer was varied to move the resonance peaks from one side of the oscilloscope screen to the other in order to get the relationship between small voltage changes and small magnetic field changes. It was found that a change of 0.005 volts corresponded to a change of 24.18 gauss in the field.

The equipment had been on for one hour before readings were taken. The test lasted six hours and 50 minutes. The results were as follows:

Batteries dropped in voltage $32.6 \times 6.2 = 202$ μ volts.

$$\left(= \frac{202}{410} = 0.493 \ \mu \text{ volts/min.} \right)$$

This drop is equivalent to drop in field of

$$\frac{202 \times 10^{-6}}{5 \times 10^{-3}} \times 24.18 = 0.98 \text{ gauss}$$

At the same time, the corrected oscillator frequency dropped

from 2×14.8619

to $2 \times 14.8580 = 0.0078$ mc/s

which is equivalent to a drop in field of 234.8×0.0078

$= 1.83$ gauss

corrections then are a fall of 2.81 gauss

The observed fall in field was 0.6 gauss

subtracting this from the above correction we get

$$\begin{array}{r} 2.81 \\ \underline{0.6} \\ 2.21 \end{array}$$

corrected rise in field 2.21 gauss

at an average field of 6,962 gauss

which is a variation of $\frac{2.21}{6,962}$ = three parts in 10,000

Appendix 2.

Thermal effects in the magnet

(a) Effect of temperature change on the magnetic field

At the beginning of the long test run the room temperature was 22 degrees centigrade while the cooling water temperature at the intake was 15.2 degrees centigrade. At the end of the test the cooling water had risen to 17 degrees centigrade.

If we assume the magnet was cooled 5 degrees centigrade after seven hours we may calculate the decrease in air gap width due to the linear contraction of the steel of the magnet.

The net linear contraction will be due to a one inch section of steel. Taking $\alpha = 10.5 \times 10^{-6}$ per degree centigrade for soft steel we find from

$$L = L_o (1 + \alpha t)$$

that $\Delta L = L_o \alpha \Delta t$

therefore
$$\frac{\Delta L}{L_o} = \alpha \Delta t$$
$$= 10.5 \times 10^{-6} \times 5$$
$$= \tfrac{1}{2} \text{ part in } 10^4$$

This will affect the flux density in the air gap directly as

$$H_{air} = \frac{\frac{4 \pi N I}{10} - H_{iron}\, l_{iron}}{l_{air}}$$

and $$\Delta H_{air} = -\frac{1}{(l_{air})^2}\, \Delta l_{air} \left[\frac{4 \quad N I}{10} - H_{iron}\, I_{iron} \right]$$

therefore $$\frac{\Delta H_{air}}{H_{air}} = -\frac{\Delta l_{air}}{l_{air}}$$

This shows that a net decrease in air gap width of $\frac{1}{2}$ part in 10,000 will cause an increase in field strength of the same amount.

(b) Estimated time for magnet to cool

This calculation is not straightforward because of the unknown factors in heat transfer from the copper coils to the cooling water and also to the steel of the magnet. However, it can be estimated with the help of the empirical information given in H. C. Roters 'Electromagnetic Devices'. The data is as follows:

Room temperature	22 degrees centigrade
Cooling water intake temperature	15.2 " "
Cooling water outlet temperature (after 7 hours)	17 " "
Total flow of cooling water	92.2 c.c./sec.
Magnet current	12.03 amperes

Resistance of copper	4.6 ohms
Weight of copper present	500 lbs.
Weight of steel of magnet	$7\frac{1}{2}$ tons.
Heat capacity of copper	180 joules /lb./degree centigrade
Heat capacity of steel	225 joules/lbs./degree centigrade

The heat energy added by the electric current is

$$(12.03)^2 \times 4.6 = 667 \text{ watts} = 667 \text{ joules/sec.}$$

The heat energy taken away by the cooling water is

$$92.2 \times 4.18 \times 2 \qquad = 770 \text{ joules/sec.}$$

This leaves a net amount of heat energy of 103 joules/sec. which is taken away from the copper and steel and thus will lower their temperature.

Considering the copper alone, to lower its temperature one degree centigrade requires taking away from it of

$$500 \times 180 = 90{,}000 \text{ joules.}$$

Therefore, if the copper is considered first alone, the time taken to lower its temperature one degree centigrade is

$$\frac{90{,}000}{103 \times 60} = 14.6 \text{ minutes.}$$

After some time, the steel becomes between 45 % and 50 % effective in absorbing heat[1]. Therefore, assuming 50 % effectiveness, the heat energy taken away to lower its temperature by one degree centigrade is

$$\tfrac{1}{2} \times 7.5 \times 2{,}000 \times 225 = 1{,}690{,}000 \text{ joules.}$$

To this, add that of the copper 90,000 joules

giving a total of 1,780,000 joules.

The time required to lower the whole magnet one degree centigrade once heat transfer had been established between the copper and steel would be

$$\frac{1{,}780{,}000}{103 \times 60 \times 60} = 4.8 \text{ hours}$$

which could only account for a drop of about $1\frac{1}{2}$ degrees centigrade in seven hours.

A complete analysis would have to take into account the thermal conductivity of the steel of the magnet followed by a solution of Fourier's heat equation for this shape of solid. It can easily be seen that the steel of the pole pieces would have to cool down before the yoke of the magnet could feel the effect of the cooling water.

An assumption that the pole pieces formed $\frac{1}{4}$ of the weight of the magnet would change the time to cool them one degree to the right amount. This would change the time to cool the copper plus the steel of the pole pieces only, to 1.4 hours for a one degree drop or 7 hours for a drop of 5 degrees centigrade.

Appendix 3.

Adjustment to the control system necessary for optimum operation

The procedure for starting the magnet is as follows:

1. Push the main toggle switch S_1 up to apply power to the amplifier and all heaters. This lights the amber indicator bulb. A five minute time delay prevents operating the H. T. relay.

2. After waiting five minutes, (or after hearing the 'click' of the time delay relay) push button S_4 whereupon the red jewel indicator shows, indicating H. T. is applied to the power unit. If the red jewel does not light, then one or more of the interlock circuits are open. These interlocks are:

(a) A toggle switch on this main panel marked 'H. T. interlock. This must be in the 'on' position.

(b) The pressure switch at the intake manifold, the cooling system. Water must be turned on and most important the water outlet tap must also be turned on.

(c) A one milliampere relay on the regulator tube chassis. This relay opens if the 6 A S 7 grids become positive.

(d) The push switch on the doors of the cabinet rack enclosing the power unit. This cabinet rack is mounted in the motor-generator room.

Now, providing all the interlocks are closed, and depending on the Rubicon potentiometer setting and D. C. level control, the generator shunt field current meter M_2 should read (and the 6 A S 7 cathode current meter M_3 if plugged into one of the jacks).

3. Now the motor generators may be switched on by pushing the two black 'on' buttons, lighting the indicator lamps. The magnet current meter M_1 should read.

Current is increased or decreased by moving the main voltage dials on the Rubicon potentiometer. After each change of setting, the D. C. level control knob should be adjusted so that balance meter M_4 reads centre. This should, at the same time cause error signal meter M_5 to read minimum. If it does not do so, then the hum balancing potentiometer (screw adjustment) mounted at the back of the D. C. amplifier power supply chassis should be adjusted for minimum reading on this meter with no signals coming in (disconnected both shielded leads to the D. C. amplifier chassis input and ground the centre terminals).

For preliminary adjustment and calibration of the

Rubicon potentiometer - see ' Operating direction special Rubicon type "B" potentiometer cat. no. 2780, serial no. 53750.' from the Rubicon Company, Philadelphia, Pa., U.S.A.

If during the above adjustments, the shunt field current meter M_2 drops to zero, and the magnet current falls while the meters on the amplifier panel, M_4, M_5 and M_6, show off balance readings, then the current overload relay (figure 9) must have been tripped, opening the shunt field circuit of the generators. This may be reset by pushing the reset button on the current regulating tube chassis. If it will not stay in, then either there is a short in the circuit which would show up by a reading greater than one ampere in M_2 or else the rheostat adjustment on the relay is set too low. This is a screw driver adjustment at the back of the current regulating tube chassis. It should be adjusted to trip at just above one ampere of shunt field current.

Appendix 4.

Use of flip-coils and fluxmeter

Field strength measurements were made with specially constructed flip-coils and a Rawson Electrical Co. flux-meter. Four coils wound on lucite forms were made up to cover the range from 10 gauss to 20,000 gauss. Each coil was screwed tightly to a long smooth board two inches wide and shimmed with corrugated cardboard strips so as to slide into and out of the one inch pole gap without turning. The board was rubbed lightly with paraffin wax so that it moved easily though fitting tightly.

A square hardwood frame with holes spaced one inch and fitted with lucite plugs was mounted over the magnet pole pieces to hold the flip-coils in any position in the gap between the poles.

Two of the flip-coils were calibrated on a magnet using a proton resonance signal to measure the field. The other two coils were then calibrated against these.

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