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SOME NOTES ON THE USE OF HALL GENERATOR PROBES FOR MAGNETIC FIELD MEASUREMENT

by

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ABSTRACT

The principles of magnetic field measurement utilising the Hall effect in semi-conducting materials are briefly examined and the use of pulsed control currents discussed.

A compact all-transistor circuit is given which will produce control current pulses of up to 5 amperes, independent of probe impedance; and the probes used with this unit are described and their construction indicated.

Measurements made on the pinch discharge assembly FAUST are presented and compared with measurements made using conventional search coil techniques.

The advantages, applications and limitations of such a system are discussed.

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1. INTRODUCTION

For any conductor carrying a current in a magnetic field a potential is developed across the conductor which is directly proportional to both the current and the magnetic field strength. This is the well-known Hall effect and the magnitude of the potential is further dependent on the value of the Hall constant for the material: R_H. This is dependent on the current carrier concentration but is constant for any given material.

Until recently the value of R_H for known materials was very small ($\sim 10^{-12}$ volts-cm/amp-gauss) and for mutually perpendicular magnetic fields and currents of the order of 1 kG and 1 kA, with a conductor thickness of 1 cm, the potential developed was typically in the microvolt region.

However, since the advent of semiconductor materials with their low carrier concentration combined with high carrier mobility, a range of materials has appeared for which the Hall constant is large enough to enable the Hall effect to be easily observed and even utilised(1),(2),(3),(4).

The materials of most interest here are the indium compounds; indium arsenide and indium arsenide-phosphide and to a lesser extent indium antimonide. For all these materials the value of R_H is of the order of 10^{-6} volts-cm/amp-gauss while the carrier mobility is quite high (allowing power to be drawn from the sample). This value of R_H is temperature-dependent as would be expected due to its dependence on carrier concentration, but the variation is small in the region considered here (0-100°C) for both indium arsenide and indium arsenide-phosphide. It is more serious however for indium antimonide which is the main reason for its more limited usage.

The possible uses of materials with a Hall constant of this order have already been fully reported(5).

In the work described here the measurement of the magnetic fields used to produce, and of those produced by, high current pulsed discharges was the main object. A survey of the available methods of measuring magnetic field strength indicated that the experimental requirements could only be met in full by using Hall generators as magnetic field probes.

2. USE OF HALL GENERATORS FOR MAGNETIC FIELD MEASUREMENT

For an infinitely long conductor (Fig.1), carrying current i amperes, which is in a uniform magnetic field whose component perpendicular to the plane of the conductor is

B gauss, a potential V_H will appear on the edges of the conductor where

$$V_H = \frac{R_H \underline{i} \wedge \underline{B}}{d}$$ d cms being the conductor thickness.

A simple model of the conductor provides a quantitave picture of the Hall effect. In a conductor carrying current i_x in a magnetic field B_z the current carriers will experience the Lorentz force

$$\underline{F} = e(\underline{E} + \underline{u} \wedge \underline{B})$$ where u is the current carrier velocity

so that

$$F_x = eE_x$$

$$F_y = e(E_y + u_x B_z)$$

$$F_z = 0$$ E_x being the applied potential producing i_x.

Initially $E_y = 0$ and the current carriers will experience a deflecting force F_y which will produce a charge separation and an electric field. Eventually the electric field so produced will be sufficient to nullify the force produced by the magnetic field and at equilibrium

$$eE_y = e\ u_x\ B_z$$

$$E_y = \frac{j_x\ B_z}{ne}$$ where n = carrier concentration

thus

$$V_H = \frac{i_x\ B_z\ R_H}{d}$$ $R_H = \frac{1}{ne}$ the Hall constant for the material

more generally

$$V_H = \frac{R_H \underline{i} \wedge \underline{B}}{d}$$

where V_H - volts; R_H - $\frac{\text{volt-cm}}{\text{gauss-amp}}$; i - amps; B - gauss; d - cms.

Thus at equilibrium the potential developed across the conductor is directly related to both the current and magnetic field. If $\underline{i}$ is accurately known therefore, a measurement of V_H will provide a measurement of B. This is the basis of the use of Hall generators for magnetic field measurements.

This simple model is still applicable when either i or B are time-variant although some limitations will inevitably be introduced.

The response of a generator to a time-dependent magnetic field will be controlled by two factors, each with a characteristic time constant. The first, τ_1(sec) is the time required for the current carriers (electrons and holes in semiconductors) to reach their equilibrium position and thus establish the stabilising Hall potential; while the second, τ_2(sec) is the time required for the magnetic field to penetrate into the generator material. For satisfactory frequency response both times should be small compared to the time in which the magnetic field is changing.

Considering the motions of the carriers in the crossed fields then these characteristic times are given by:

$$\tau_1 = \frac{1}{\mu ne}$$

$$\tau_2 = \frac{a^2 \cdot \mu ne}{c^2}$$

where a is the width of the semiconductor element and μ the carrier mobility. This is based on the assumption that the electrons and holes have equal mobilities. For the indium compounds considered here, these mobilities differ only by a factor of two or three so that the discrepancy is not serious. For a typical element the values will be: a = 0.1 cm: $\mu = 2.5 \times 10^4$ cm^2 - volt^{-1} - sec^{-1}: $n = 2.5 \times 10^{16}$ cm^{-3} giving $\tau_1 \sim 10^{-12}$ sec and $\tau_2 \sim 10^{-11}$ sec. On these grounds therefore the generators should respond to frequencies up to 1000 Mc/s and any frequency limitations are more likely to be set by external factors (such as inductive pick-up in the probe, and response times of the measuring circuit) than by the speed of response of the generator itself. For the examination of repetitive reproducible phenomena which can be examined by pulse sampling methods, then the generator itself may set a frequency limit. The use of Hall generators with a resonant frequency of 240 Mc/s has been reported(6).

If the magnetic field is oscillatory the conductor will have eddy currents induced in it and these will modify the current in the conductor both in magnitude and distribution. Also the fields associated with these eddy currents and the original current will modify the potential produced by the original field. These effects are obviously of the second or higher orders and an approximate analysis(7), verified by experimental work, shows that unless the magnetic field is extremely well coupled to the semiconductor plate (i.e. if it is bedded in ferrite without any air-gap) they are not observable. An extension of these calculations(8) shows that, in the uncoupled case, the Hall potential signal will be in error by < 1% at frequencies up to 5000 Mc/s and the more serious limitation of phase difference will be the major restriction becoming a phase lead (of signal over applied field) of > 1° at frequencies > 500 Mc/s.

In practice the current i (or control current i_c as it is usually known) is taken into and out of the semiconductor plate, which is usually of the order of 0.01 cms thick, by means of metallic electrodes fixed to the ends (Fig.2). This reduces the risk of overheating at the contacts due to too high a current density and increases the maximum current permissible. To minimise the voltage induced in the loop formed by the leads used to take off the Hall voltage, use is made of non-inductive twisted wiring and the lead is carried across the semiconductor plate as nearly as possible on the line of the equipotential on which the contacts lie. With care in manufacture this loop can be kept small and for commercially available generators is usually less than 0.05 cm^2.

For a magnetic field B, at an angle θ to the plane of the generator, the directional sensitivity can be obtained by considering the components of the field (i) normal to, and (ii) in the plane of the generator. From the analysis above it will be seen that only the normal component, $B \sin \theta$, will contribute to the Hall potential, the other component having no effect. This has been verified experimentally by rotating a Hall generator probe through 180^0 in a steady magnetic field and plotting the signal amplitude against rotational alignment. These results are given in Fig.3; the $\sin \theta$ dependence is clearly evident.

3. THE HALL GENERATORS USED

The probes used have all been based on the commercially available Hall generators which are illustrated in Fig.4. The semiconductor plate and its contacts are encapsulated in an epoxy resin and the whole unit is extremely compact. The type FA 22e generator proved to be suitable for most applications although for the most sensitive work the type FC 32 was used. The FC 32 generators illustrated were specially produced to our specifications with non-standard leads 100 cms in length. This facilitated the assembly of probes with minimum overall diameter to suit the small-bore probe ports on the FAUST apparatus(9). The types FA 22e and FC 32 generators are essentially flat slabs of semiconductor with the control current flowing in the plane of the slab and the field direction being perpendicular to that plane. The SBV 525 generators are rather more specialised because the field direction is in the axis of cylindrical symmetry; and consequently they are rather less suitable for use in the manufacture of the type of probes normally required for discharge work.

4. THE PULSED CONTROL CURRENT MODE OF OPERATION

The continuous control current rating for most generators is of the order of 100 mA in still air and at this current the sensitivity is usually about 5-10 mV/kG. This rating is determined solely by the heat loading in the semiconductor material and the dissipative properties of the encapsulating medium, and a small advantage is gained by air-blast cooling. However, as shown above, the effectiveness of the generator will be unaffected by the use of periodic or pulsed currents and this offers a simple way of increasing sensitivity albeit at the cost of reduced time available for measurements. As these probes were required for the measurement of transient phenomena occurring in discharges it was obvious that a pulsed current source would be advantageous, and initially a simple current amplifier circuit was used to amplify a rectangular pulse. The pulse length was variable from 0-50 µsec and the unit delivered a pulse of current amplitude 2 amperes to the FA 21 generators which were used in the original investigations (these FA 21 generators are now obsolete and have been superseded by the type FA 22e). This system proved the versatility and potential of pulsed current sources and these investigations were therefore continued. The constant current circuit in Fig.5 (designed by G.L. Godfrey of this Laboratory) was developed which is capable of providing five pulses from one to five amperes in one ampere steps and of forty to ten µsec duration respectively.

The constant current design is required because the semiconductor material of the generators is magnetoresistive and a resistance change of as much as +50% is produced by a field of 10 kG. As fields of this order are frequently met with in discharges the constant current design must be adopted.

The circuit design and mode of operation is as follows.

The initial D.C. conditions are that J_2 and J_5 are conducting, whilst J_1, J_3, J_4, J_6 and J_7 are cut off.

The paralysis generator J_1 J_2 is triggered by a positive pulse fed via D_1 and D_2 to the collector of J_1 and then to the base of J_2 via the 4 µF coupling capacitor. The circuit limits the maximum frequency of the pulses produced at the collector of J_2 to about 20 c/s. This ensures that the probe element is not overheated.

These pulses are fed via J_3 to the main pulse generator J_4, J_5. Negative pulses with durations of approximately 10, 20, 30, 40 or 50 µsec (selected by SWB) are produced at the collector of J_5. These pulses turn on the output transistors J_6 J_7 for the selected time.

The current which flows in the collector of J_7 is determined by the value of the emitter resistor and the voltage developed across it by the driving transistor J_6.

SWB enables currents of approximately 5, 4, 3, 2 or a amps to be selected, these currents being tied to pulse widths of approximately 10, 20, 30, 40 or 50 μsec.

The output impedance at the collector of J_7 is high, thus providing a source of constant current.

The 1 Ω resistor in series with the output enables the output current to be monitored.

The five types of pulse available are illustrated in Fig.6; an oscillogram on which they are superposed. An examination of these pulses using a comparator preamplifier in an oscilloscope shows that the current amplitude during the pulse is constant to better than 2%. The degree of drift observed over a 12 month period is less than 1%. One further restriction which is worsened by the mode of high-current pulsed operation is the existence of a zero-field signal. The contacts used to collect the Hall potential should ideally lie on an equipotential between the control current contacts but physically this is impossible to achieve. This gives rise to a small resistive voltage which is superposed on the Hall potential, but which can be balanced out by a network system such as that of Fig.7, which was used in conjunction with our FA 22e and FC 32 probes. The terminating resistor R_L is the value required to give maximum linearity of response (usually better than 1%) between the signal voltage and the magnetic field producing this voltage. This should be of the order of ten times the Hall generator internal resistance measured across the Hall voltage contacts.

For the most accurate work the effect on the signal caused by any temperature variation can be easily eliminated by using a temperature compensating network(10). As the Hall voltage has a negative temperature coefficient it is necessary to use a network which has a positive temperature coefficient. Thermistors are convenient components for this purpose.

5. THE PROBES USED - CONSTRUCTION AND OPERATION

The generators were mounted in an insulating holder at the end of a small diameter brass tube which served both as a rigid support and an electrostatic screen. For the search coil/Hall generator comparison probe a small rectangular search coil was mounted on the Hall generator so that the area of the coil was as nearly as possible the same as the sensitive area of the generator. The end of the brass tube was mounted on a flange on a small aluminium box containing the balancing net, the sockets for the control current supply and the signal lead to the oscilloscope (and the search coil signal output socket where required).

The control current pulse generator fed the probe via 14 Ω impedance co-axial cable while 100 Ω balanced twin feeder was used to transmit the Hall voltage signal to a differential preamplifier unit at the oscilloscope. The latter system is essential since the control current utilises an earth return and thus one side of the Hall generator is already grounded.

For all operations it was found convenient to trigger the control current unit via a delay unit to allow the control current pulse to be accurately positioned in time. The block diagram for this mode of operation is given in Fig.8.

6. VACUUM FIELD MEASUREMENTS

The Hall probes described above were used extensively on the FAUST 1A apparatus to determine the vacuum field profiles. The three field systems on this apparatus had markedly different characteristics from each other:

(1) A fast axial field produced by a single turn thetatron like coil connected to a fast 600 μF capacitor bank by 10 spark-gaps. The field had a risetime (quarter period) of 14 μsec, with a maximum value of 6 kG.

(2) The azimuthal field was generated by a hardcore-return conductor system connected via a transformer and ignitrons to a 3120 μF capacitor bank. The risetimes of this field could be varied between 200-650 μsec and the maximum current available was 150 kA.

(3) A large diameter solenoid, co-axial with the single-turn coil, connected to a 1560 μF capacitor bank by ignitrons produced a slow axial field. This had a risetime of 80 msec with a maximum value of 2 kG.

One of the calibration requirements was to determine the radial profile of the azimuthal and fast axial fields in the central radial plane of the tube where diagnostic measurements were made and at the same time to measure the value of the slow axial field in the same region. The same field measuring device was to be used, if possible, for all these sets of measurements to reduce the cross-calibration difficulties, and the FA 22e Hall generator probe was chosen for this purpose as the frequencies to be covered were well within its normal working range.

To illustrate this set of measurements the radial profile for the vacuum azimuthal field as measured by this probe is shown in Fig.9, along with the theoretical field distribution for a 135 kA rod current with return current carried by a continuous cylindrical conductor. The position and layout of the hardcore rod and the return current straps are also shown. The departure from the theoretical model is due entirely to the return current being carried by sixteen straps rather than a cylindrical conductor as in the theoretical case, and to which the strap system is an approximation.

The fast and slow axial fields were also calibrated using the same probe and the cross-calibration was therefore achieved without the need for using different devices as would have been the case with the conventional search coil technique.

The sensitivity of the pulsed control current mode can be used to map a slowly varying magnetic field by repetitive pulsing of the control current during the period of the field pulse. The use of this technique is illustrated in Fig. 10. The lower trace is that of the potential developed across a resistive load in series with a solenoid when a small capacitor bank is discharged into the predominantly inductive load; it therefore represents the magnetic field waveform. The envelope of the pulses in the upper trace is clearly that of the magnetic field waveform. In this case the field of frequency of 150 c/s is adequately plotted using 50 μsec control current pulses.

7. DISCHARGE FIELD MEASUREMENTS

In order to evaluate the relative merits of the Hall generator and search coil probes, a multiple probe was constructed with a Hall generator and a search coil mounted alongside each other so that their sensitive areas were as nearly equal as possible. Using this probe a series of measurements was made in the FAUST B inverse pinch apparatus, to determine the radial distribution of the azimuthal magnetic fields as a function of time. This is a measurement frequently made in pinched plasma systems and is a reasonable test for comparison purposes(11).

The results are indicated in Fig. 11 where the radial profile of rB_θ (r - radial position in cm: B_θ - azimuthal magnetic field in gauss) at t = 15 μsec is plotted. This time was chosen as it coincided with maximum current in the plasma. Within the limits of experimental error both the search coil and the Hall generator give the same results. During preliminary measurements it was found that considerable care had to be taken to avoid any inductive loops in the Hall generator circuit.

Fig. 12 is an oscillogram of the axial magnetic field in the centre of the current channel; the lower waveform being the Hall voltage and the upper the integrated output from the search coil. The sharp cut-off in the lower trace is due to the control current pulse switching off. The superior frequency response of the Hall generator probe is also evident in its resolution of the low amplitude, high frequency field fluctuations which start a few microseconds after the waveform has reached its peak value. These fluctuations are undetected by the search coil probe.

These measurements exposed the major weakness of Hall probes for discharge field measurement, namely the presence of an inductive signal component in the output. With a rate of change of magnetic field of 500 G/μsec even a low inductance probe will have a 50-100 mV signal induced in it and this may well be a significant proportion of the total output. Such a rate of change of field is often met with in plasma physics work and must therefore limit the usefulness of these devices. Special techniques of manufacture or special selection of the generators could overcome the problem but would also increase the cost of the items.

8. DISCUSSION

A direct comparison between the two systems of measurement is realistic only if one allows that, due to cheapness and ease of manufacture, a search coil can be tailor-made for any particular measurement as and when required. This in fact is the usual approach when using coils and seldom is an attempt made to produce a "universal" search coil which will cover the full range of measurements that may arise in the course of an experiment.

If this assumption is accepted then the greatest advantage of the Hall generator probe is immediately apparent; that is, its large range of application. This has the further advantage, from the experimenters point of view, that the lengthy and difficult problem of accurate probe calibration is reduced to the simplest level, i.e. calibration of one probe only.

Advantages common to both systems (and indeed usually taken for granted in the case of pick-up coils) and included here for the sake of completeness are:-

(1) probes can be constructed on a small scale and thus measurements of fields with high gradients can be made.

(2) probes can generally be treated as low impedance sources and should have a lower noise level than other higher impedance systems.

(3) long-term stability of probes is excellent.

(4) with care in calibration the accuracy of probes can be very high.

The Hall generator probes have the further advantages which are not possessed by coil probes:-

(1) a single probe should suffice for measurements in the frequency range D.C. → > 200 Mc/s without any modifications.

(2) the probes are direct reading and require only a voltage measurement.

(3) if used in the pulsed mode of operation the time at which the probe is sensitive to magnetic fields can be accurately controlled.

(4) by varying the control current through the probe (whether D.C. or pulsed) the sensitivity can be varied.

(5) higher sensitivities are more easily obtained, 500-1000 mV/kG being quite common with 5900 mV/kG having been reported.

Against these advantages the following disadvantages must be considered:-

(1) like all semiconductor devices they are sensitive to overheating, are relatively expensive, and require specialised techniques for their manufacture.

(2) a source of control current is required; in the D.C. case a battery or commercially available D.C. power supply is sufficient but for pulsed operation a specially designed pulse generator (such as that described above) is necessary. These sources, whether pulsed or D.C. will introduce uncertainties into the measurement.

(3) the semiconductor material is magnetoresistive and its Hall constant is temperature dependent. The former can be overcome by means of constant current operation while the latter can be eliminated if accurate work is required, the variation being small in the range usually met with in probes, viz. 0-100°C. The method of manufacture also leaves a small resistive voltage in the form of a zero-field component which must be eliminated before the probe is used. This is easily done with a potential divider network.

(4) where the probe is used in a magnetic field which varies rapidly with time the presence of an inductive signal component may become serious.

In general an accurately calibrated Hall generator probe together with both a variable level of D.C. and a pulsed control current source is an extremely versatile field measuring device. For simplicity the search coil and RC integrator system still takes first place but only if a limited frequency range is being considered. In general the Hall generator probe is to be preferred whenever an extended series of measurements is to be made.

9. ACKNOWLEDGEMENTS

The author is grateful to Mr G.L. Godfrey of the Culham Laboratory Electronics Division for the design of the constant current pulse circuit; and to Mr B.A. Ward for many helpful discussions on this and related topics.

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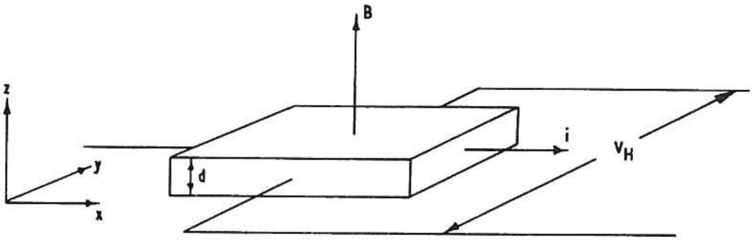

Fig. 1 Basic layout of Hall generator (CLM-M48)

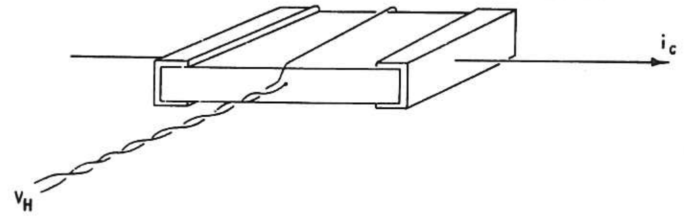

Fig. 2 (CLM-M48)
Practical layout of leads and electrodes for a Hall generator

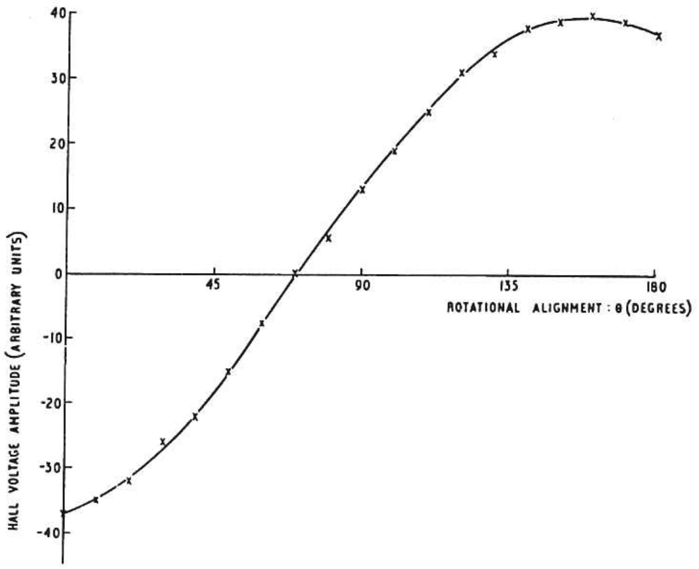

Fig. 3 (CLM-M48)
Directional sensitivity of Hall generator probe

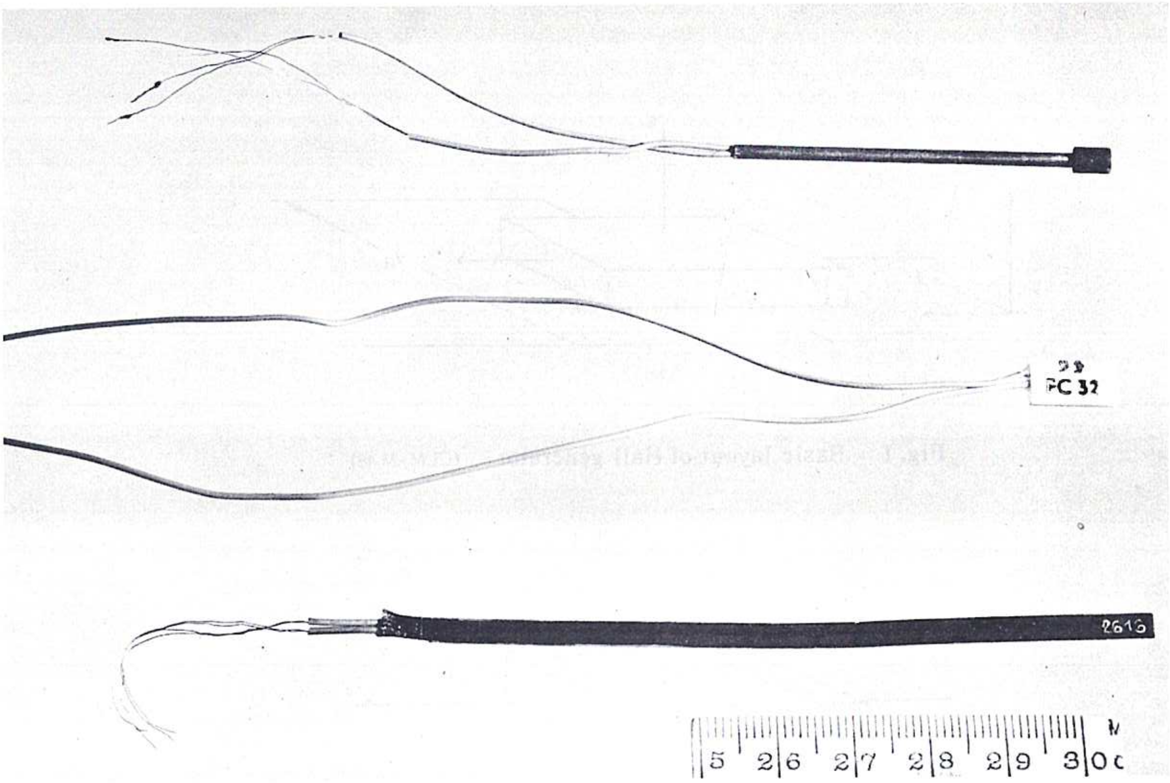

Fig. 4 (CLM-M48)
The Hall generators used. The types illustrated are
(a) SBV 525, (b) FC 32, (c) FA 22(e)

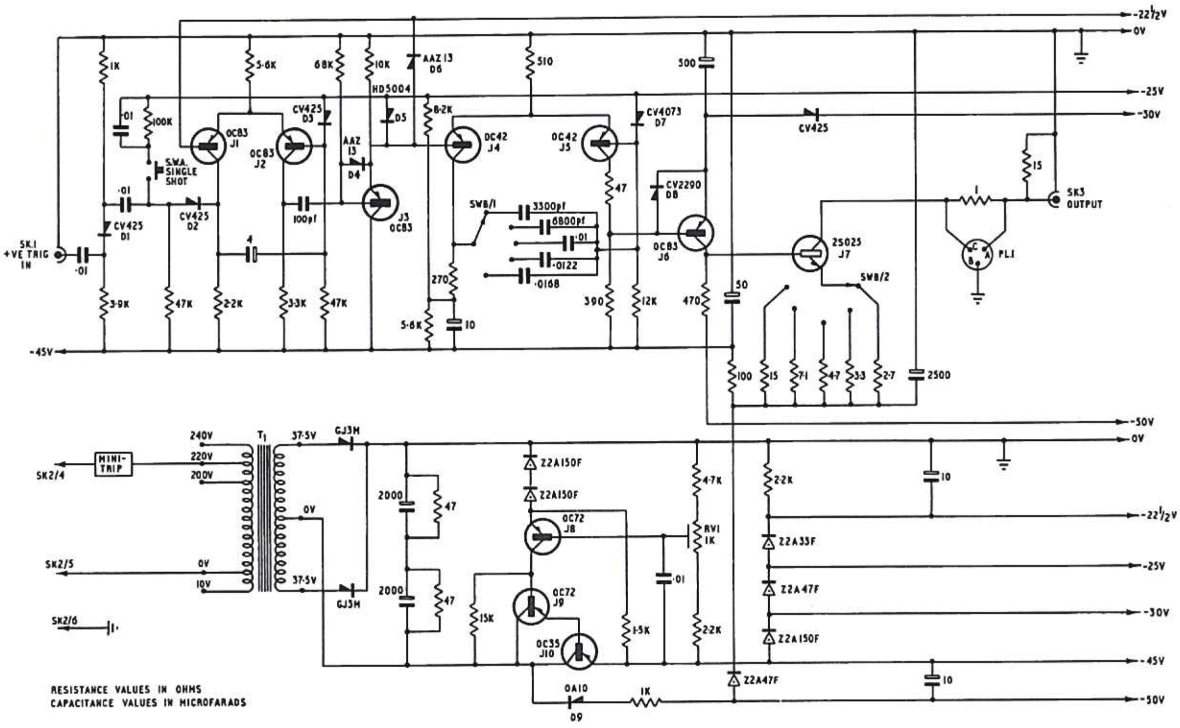

Fig. 5 Current pulse generator (CLM-M48)

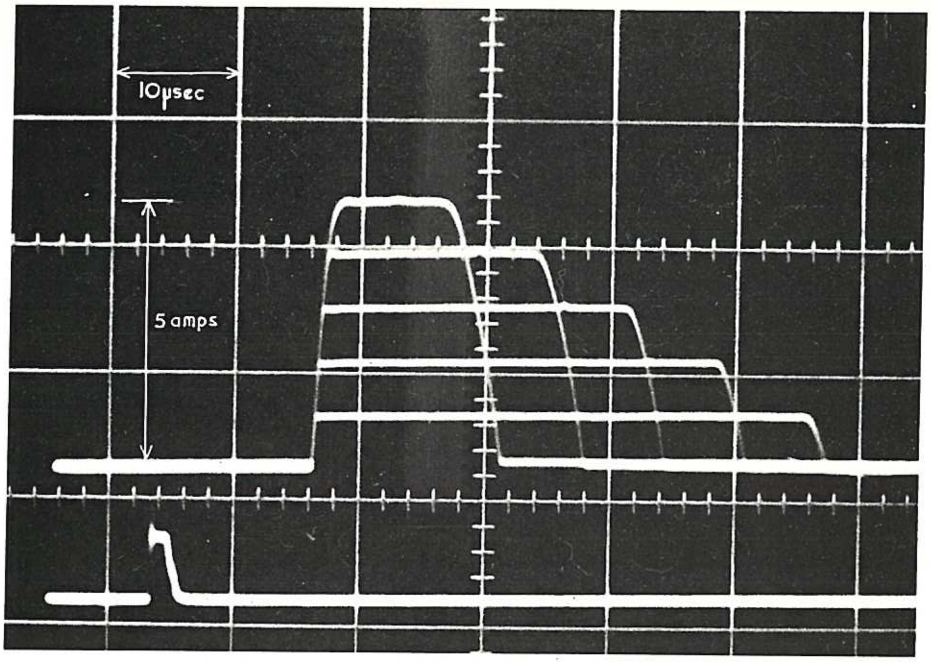

Fig. 6 (CLM-M48)
Output pulses from the current pulse generators; the five pulses available are superimposed in this oscillogram

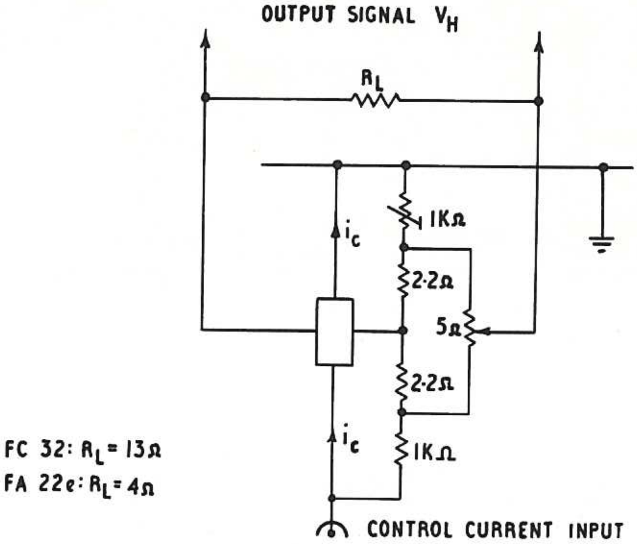

Fig. 7 (CLM-M48)
Resistive signal elimination network used with FC 32 and FA 22(e) probes

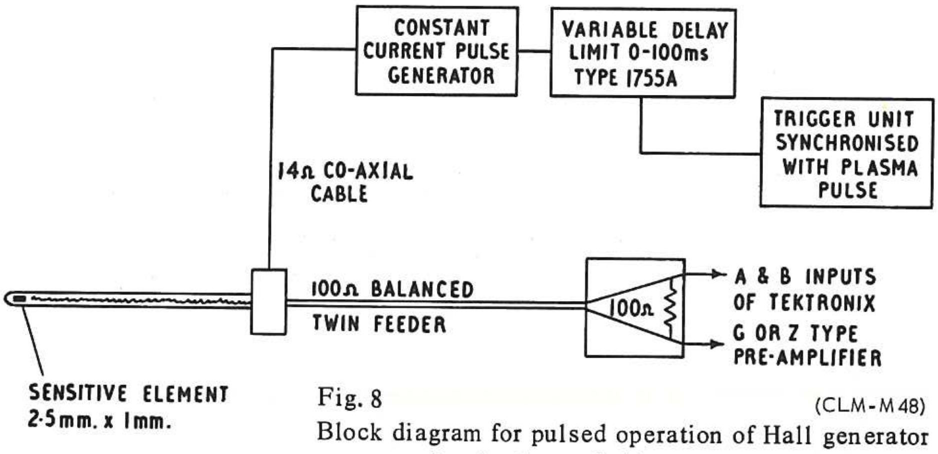

Fig. 8 (CLM-M48)
Block diagram for pulsed operation of Hall generator for discharge field measurements

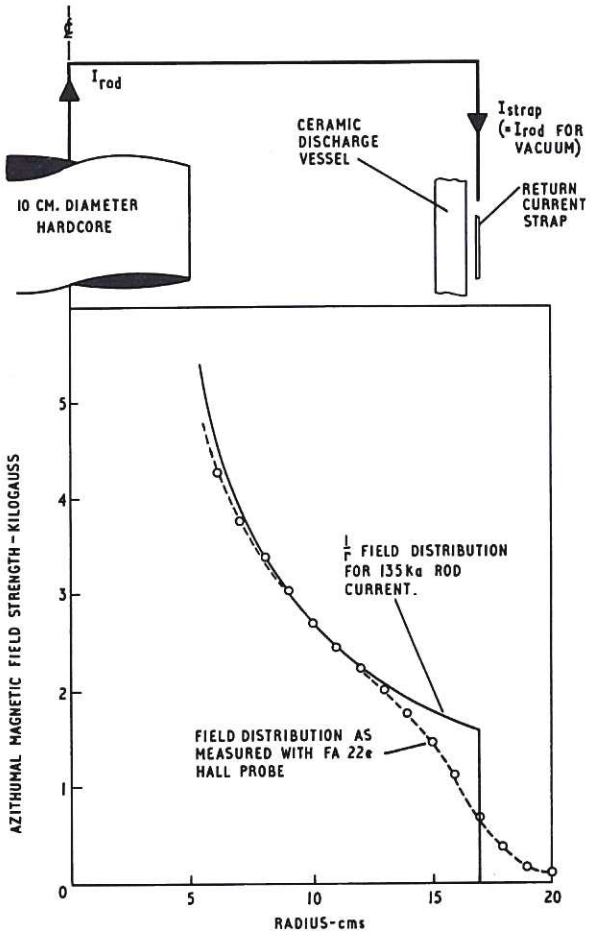

Fig. 9 (CLM-M48)

Expected and measured azimuthal magnetic field in FAUST 1A : with hardcore and return strap system

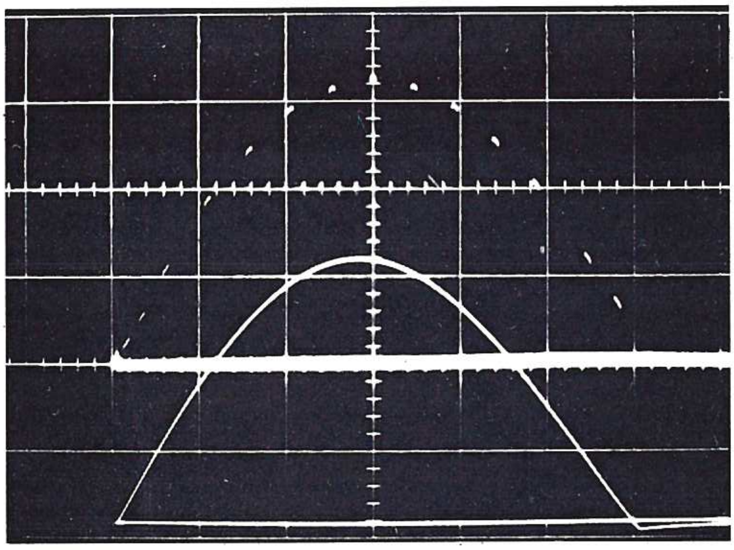

Fig. 10 (CLM-M48)

Use of repetitive pulses of control current to measure a d.c. or low frequency field

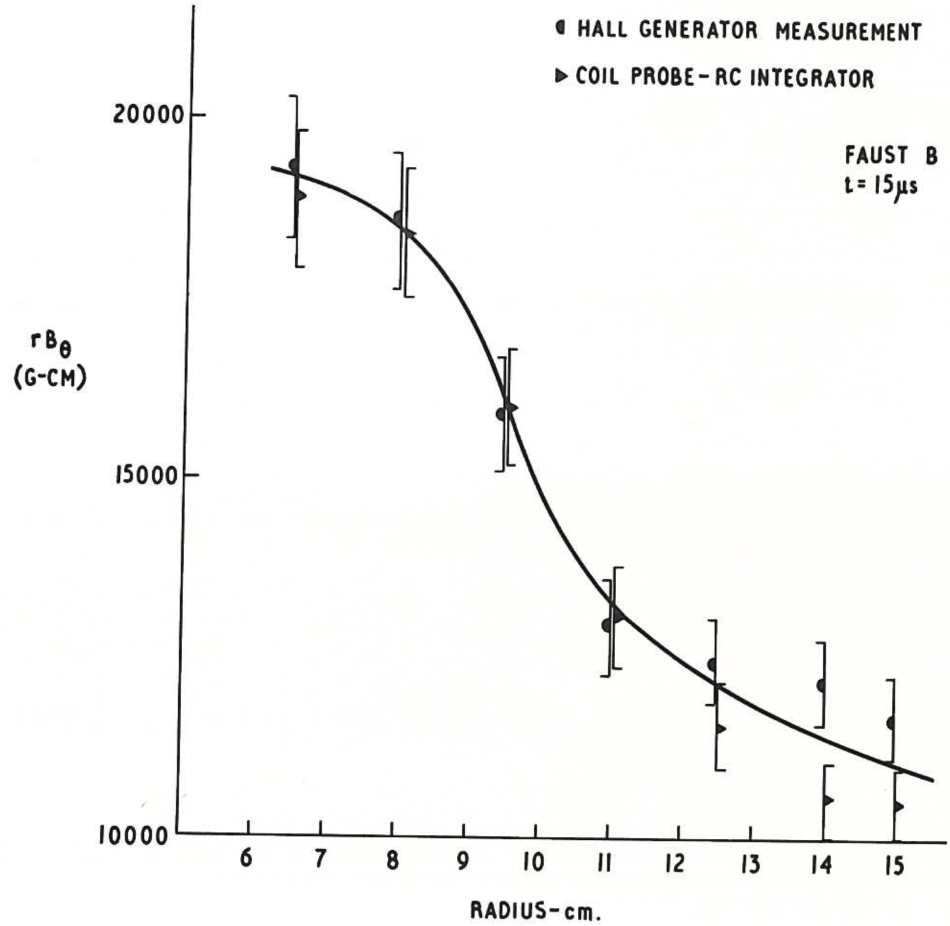

Fig. 11 (CLM-M 48)

A FAUST B rB_θ discharge profile measured with a Hall generator and a search coil probe

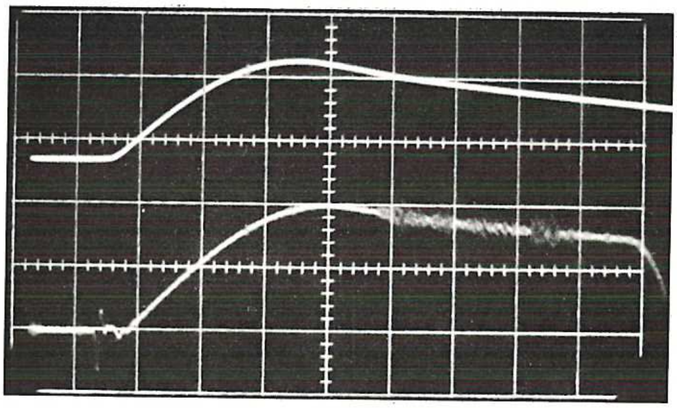

Fig. 12 (CLM-M 48)

Oscillogram of integrated search coil output and Hall voltage signal