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EIGHT-INCH APERTURE SUPERCONDUCTING COILS

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EIGHT-INCH APERTURE SUPERCONDUCTING COILS

by

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ABSTRACT

Tests on the first sections of a superconducting magnet coil, suitable for a mirror containment experiment, indicate that, although the performance is below that expected and falls off with increasing coil size, the removal of stored energy from the low temperature region is both practicable and worthwhile.

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INTRODUCTION

Plasma physics research requires large magnetic fields at densities of up to 50 kG and more. If they can be generated by superconductors operating at a high current density, considerable economic advantages could be gained.

In addition to investigating the properties of presently available materials and the problems of coil degradation, a study of the problems associated with large coils is being undertaken. Construction, protection, conservation of helium and the cryogenic engineering required to contain a pair of superconducting mirror coils is included in the study. The first stage, covering the construction and testing of a number of pancake coils in a simple test cryostat, is described here. Fig. 1 shows an assembly of 4 spools ready for insertion in the cryostat.

COIL CONSTRUCTION

The major coil parameters are illustrated in Fig. 2 whilst the details of each spool are given in Fig. 3.

WIRE

Copper plated Niobium_{75} Zirconium_{25} wire was used with dimensions as follows:-

Diameter over superconductor - 0.010"
Diameter over copper plating - 0.013"
Diameter over insulation - 0.014"

As received from the manufacturer the wire suffered from flaws in the insulation and asperities in the copper plating. Fig. 4 illustrates one such defect.

Checks carried out during the winding of the first spool showed that short circuited turns appeared as the winding progressed. The wire used in the first 4 coils was therefore additionally insulated by lapping with 0.001" Melinex 1 mm wide, 50% overlap to give an overall wire diameter of 0.018".

INSULATION

The method adopted for removing the stored energy from the coil at quenching causes a high voltage to be generated across the coil. The coil was therefore designed to operate at a maximum voltage of 5 kV as follows:-

(a) At the bottom of the winding space, 17 turns of Melinex are wound on to the former and petalled up the end cheeks for 11/16", the end cheeks being recessed to take the petalling.

(b) The sides of the former are insulated by 1/32" S.R.B.P. washers.

(c) The wires at entry to and exit from the former are sleeved with 0.02" thick P.T.F.E. and pass into the former through rigid transparent P.V.C. inserts.

(d) Interlayer insulation takes the form of 0.00025" Melinex sleeved round the end turn of each layer, as shown in Fig. 3. This arrangement prevents displacement of the end turns and gives a self-supporting winding which could, with the need for a better space factor, be used on a former from which the end cheeks are removed after winding.

(e) No form of consolidation is used in winding the coil other than the Melinex sleeving, and there is no support for the coil tails other than loose taping to the coil support structure.

FORMER

A brass former is used, being a compromise between thermal and electrical requirements. Good thermal conductivity is needed during cool down, but low electrical conductivity is required to minimise eddy current heating during current decay.

WINDING

Each of the first four spools has between 4,900 and 5,000 turns, giving a length of wire of about 13,000 feet and a calculated normal inductance of 8.5 Henries. The space factor of the winding alone is 0.193: of the winding and former together the space factor is 0.134. The resistance at $11^{\circ}K$ is about 60 ohms. Connections between the sections of each spool and between spools are resistive (about 1 $\mu\Omega$) and are made, as are the current terminals, by clamping the wire between indium-coated copper blocks. The wire under the block is stripped of insulation and copper and "friction-tinned" with molten indium.

Wire from a different manufacturer, and from which the copper asperities had been removed, was used for the 5th spool. The wire was not additionally insulated and as a result it was possible to increase the number of turns to 8,120.

CONTROL AND INSTRUMENTATION

The coils are energised by a battery in a simple L-R circuit as shown in Fig. 5.

In order to conserve liquid Helium and to reduce the "cool-down" time following quenching, a large proportion of the energy stored in the coils is extracted and dissipated externally.

The onset of quenching results in a fast rising voltage within the coil. The voltage is sensed at two points in the coil with respect to the centre tap which is earthed. One sensing point is at one end of the coil; the other is near to the centre tap. The latter will detect quenching which propagates symmetrically about the centre tap.

The signal is differentiated to discriminate it from the more slowly changing charging voltage across the coil. It is then passed through a limiting circuit to a chopper amplifier. The output from the amplifier trips a bistable circuit controlling the vacuum switches.

To a limited extent the detection system is monitored and interlocked to guard against failure of the amplifiers, but the system is inherently not "fail-safe" and requires careful checking. For this purpose a heater has been incorporated in each spool so that quenching may be started artificially at a low current to check the functioning of the detection and control circuits.

The overall delay in opening the vacuum switches is 10 msec. Of this, 8 msec results from inertia in the switches and there is 2 msec of delay in the chopper amplifiers.

The energy dissipated within the coil at quenching is related to the total time of propagation of normality. Consequently the discharge resistance must be as large as possible, its maximum value being limited by the insulation level of the coils, in this case, 5 kV. By using a non-linear resistor, whose resistance rises as the current falls, the voltage across the coil can be maintained close to 5 kV so that the current decays more rapidly than it would if a constant resistance were to be used.

A specific test showed that in four spools together, quenching at 8 amperes, only 7% of the stored magnetic energy is released in the normalised wire.

CRYOGENICS

Two concentric dewars are used to take the coils and to provide nitrogen shielding. Baffles, in heat exchange with evaporating helium vapour, provide temperature grading within the inner cryostat. This allows a short assembly to be used; in the present case the inner cryostat is 30 inches deep.

Helium transfer is through liquid nitrogen shielded transfer tubes. Fifteen litres of helium are required to cool an assembly of four spools from 78°K to 4.2°K. The boil off rate whilst testing the coils is about three litres per hour.

RESULTS AND OBSERVATIONS

FIELD AND CURRENT

The maximum value of current, central field and maximum field obtained with the various combinations of spools were as follows:-

Spool No.	Current Amps	$H_{central}$ kG	H_{max} kG
1	29.0	6.90	17.25
2	28.0	6.66	16.67
3	25.6	6.08	15.23
4	29.5	7.01	17.55
1+2	20.0	9.26	17.60
1+2+3+4	12.3	10.40	14.40
5	19.0	7.50	18.80

FLUX JUMPING

Signals, ascribed to flux jumping, were generated within the coils during current rise. The amplitudes of these signals were in some cases sufficient to trip the protection circuit but not to cause quenching.

In general the amplitude of these signals both in terms of peak voltage and volt-seconds, increased with increasing current and with the number of spools being energised. Also when one spool only was energised in a pair of spools, flux jumping was of greater amplitude than in one isolated spool. Reversing the current in a spool after energising in one direction produced more violent flux jumping than appeared with the initial direction of current.

Typical amplitudes of flux jump signals as measured across one half of the coil or set of coils were as follows:-

No. of Spools	Current Amps	Peak amplitude Millivolts	Signal envelope mV secs
1	20	140	.01
4	11.4	2500	58

TRANSITION TO NORMAL STATE

Difficulty was originally encountered in trying to obtain oscillograms of the voltage developed at a quench. When the oscilloscope was arranged to trip from the flux jump signals it was found impossible to differentiate between the signal immediately before the quench and the many signals preceding it. Tripping at the instant when the vacuum switches opened was also unsatisfactory because of the 10 msec delay in opening. On the later tests, therefore, an instrument-type tape recorder has been used. At present this is limited to one Direct and one F.M. channel. The Direct channel responds to the upper frequencies and the F.M. to the lower ones, giving a total coverage from 100 kc/s down to d.c. In addition to performing the task of delaying the signal the recorder also serves a useful purpose in storing all the signals obtained during a test run. They can then be examined at leisure at a later date when the expense of continuously boiling helium is absent.

Fig. 6 shows the signal obtained across half of one spool. The initiating flux jump is shown on the Direct channel and the F.M. shows the propagation of normality.

The top trace of Fig. 7 shows the F.M. signal obtained as normality propagated in an assembly of four spools. The lower traces are of the same event but on an expanded time scale. These suggest that normality was initiated not by the large signal but by the relatively small signal occurring 50 msec after the commencement of the large one.

Similar oscillograms also showed in which part of the coil the transition commenced. When testing spool no. 5 alone, for instance, it was found that quenching started in the inner half 18 times and in the outer 3 times.

RATE OF RISE OF CURRENT

One spool was energised at two rates of rise of current; 0.4 amps/sec and 0.04 amps/sec. In these two cases there was no significant difference in the maximum currents obtained.

OPERATION AT ELEVATED TEMPERATURES

Four spools were tested individually in helium gas at temperatures between 4.2°K and 11°K. The maximum currents attained are plotted in Fig. 8.

COMMENTS

With care, coils having uniform performance can be built. Their performance, however, is well below that expected from short samples, and degrades further as spools are stacked together.

It is interesting to note that the current in coil no. 5 degrades until the field produced is little better than that from each of the other coils. Indeed, the value of maximum field is almost independent of the number of spools energised.

The results so far obtained show that, for coils of the size tested, the removal of a large part of the stored energy from the low temperature region is practicable and worthwhile.

Electrical signals attributed to flux jumping increase with the coil size. This may set a limit to the size of coil in which the present method of quench detection is satisfactory.

The coils operated at least as well when in helium gas as when in the liquid. This may indicate that even if a coil is totally immersed in liquid helium, at the instant of quenching there are regions of the wire not in contact with the liquid.

The temperature curves also indicate that there is an optimum operating temperature at about 5°K.

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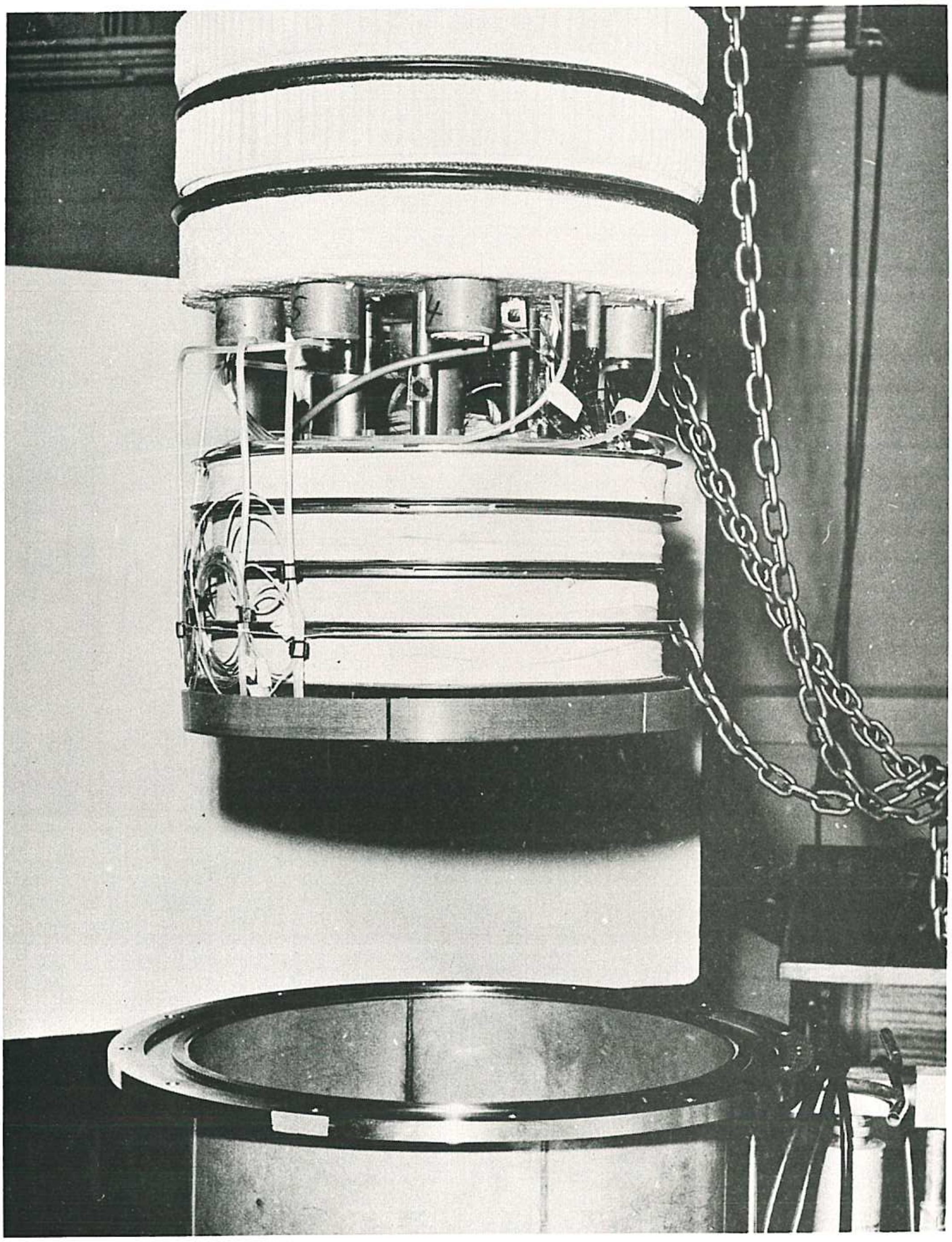
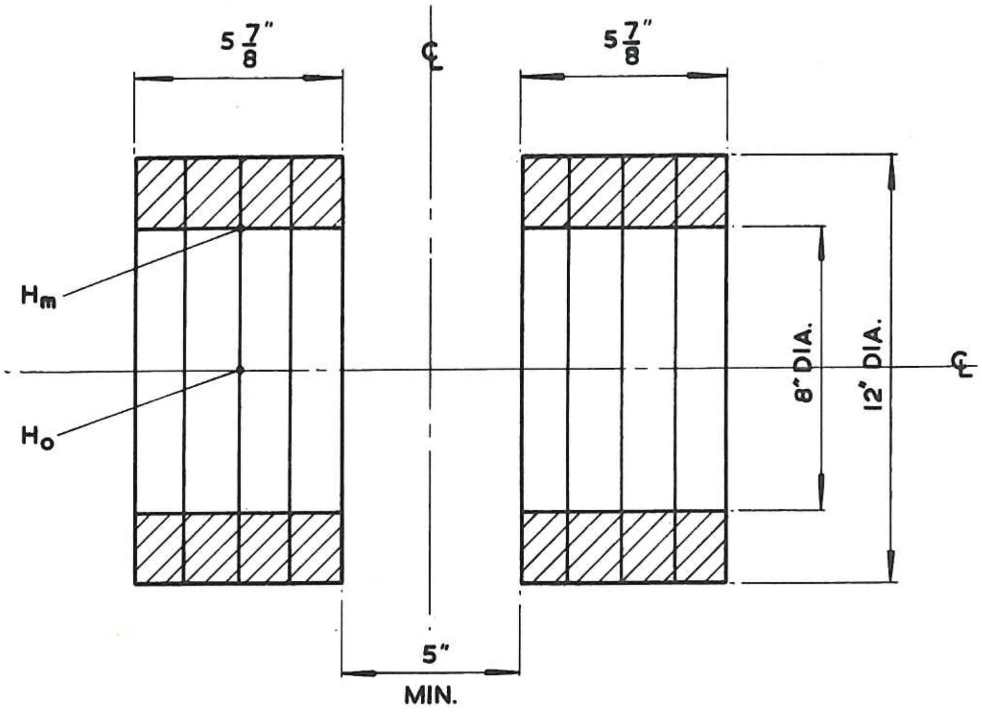
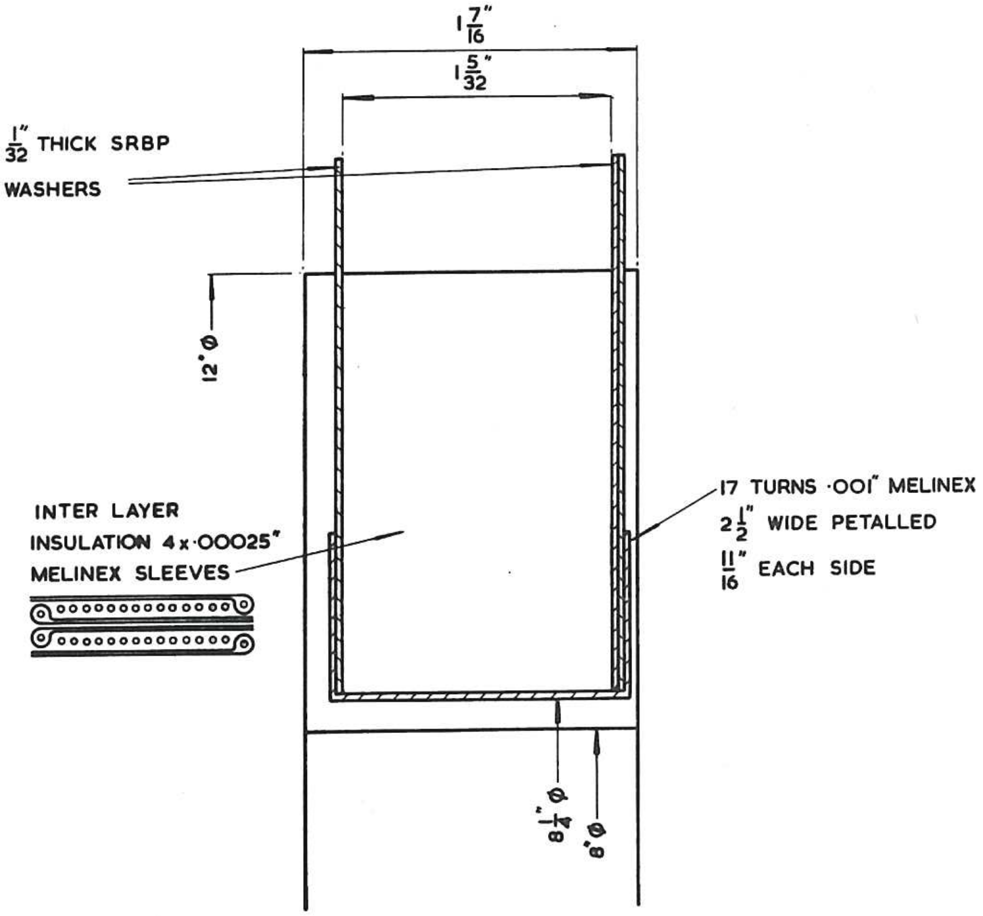
The valuable assistance of Mr. J. Morrison in the laboratory is also acknowledged.



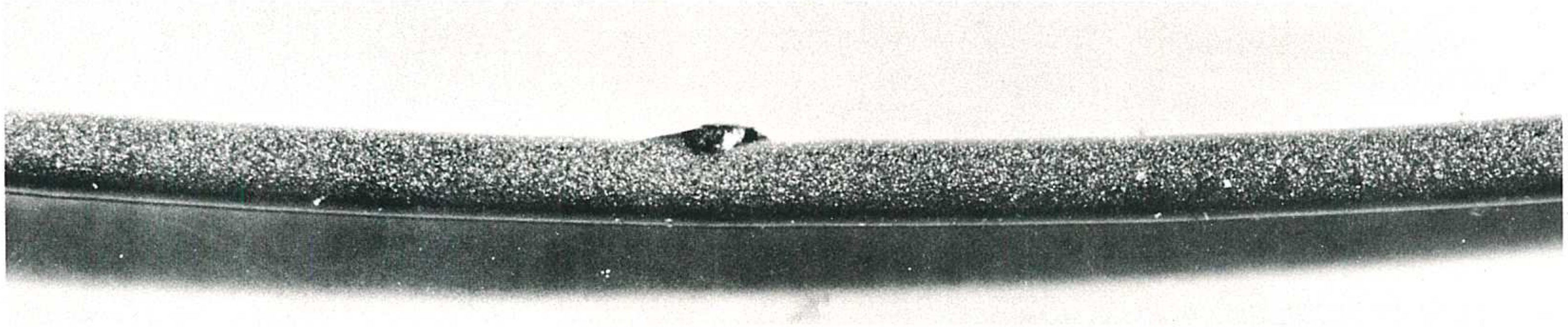
CLM-P 51 Fig. 1 Assembly of four pancake coils



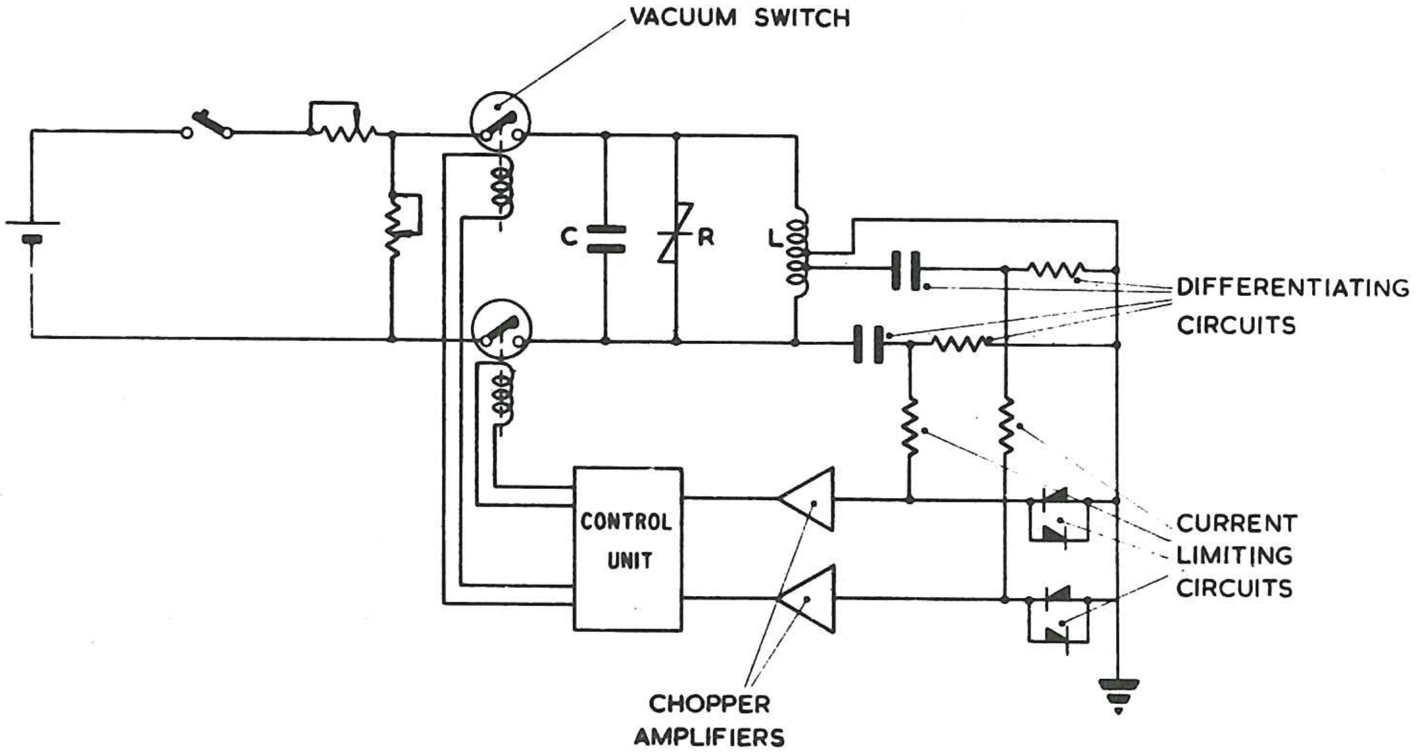
CLM-P 51 Fig. 2 Overall coil dimensions



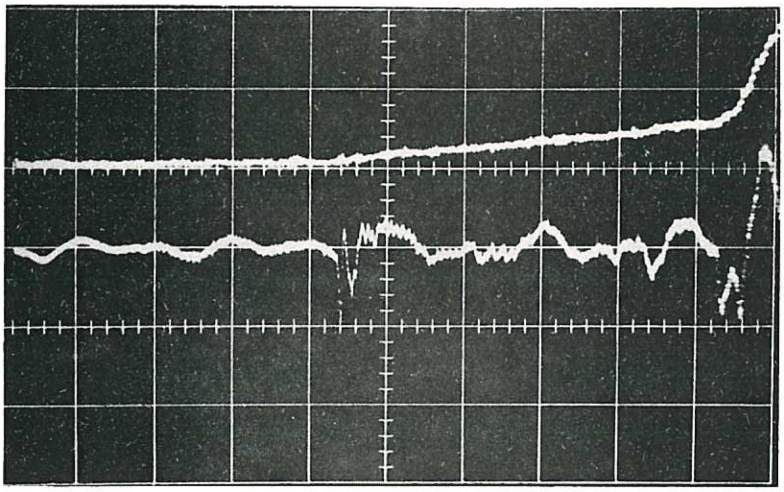
CLM-P 51 Fig. 3 Insulation between winding and former



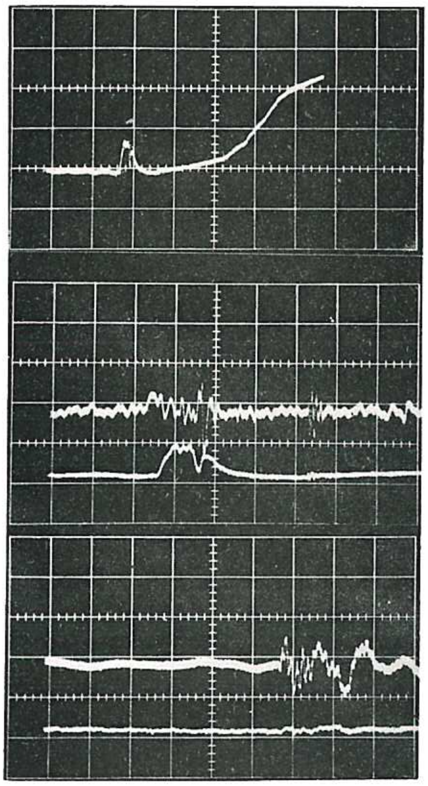
CLM-P 51 Fig. 4
Copper asperity on superconducting wire



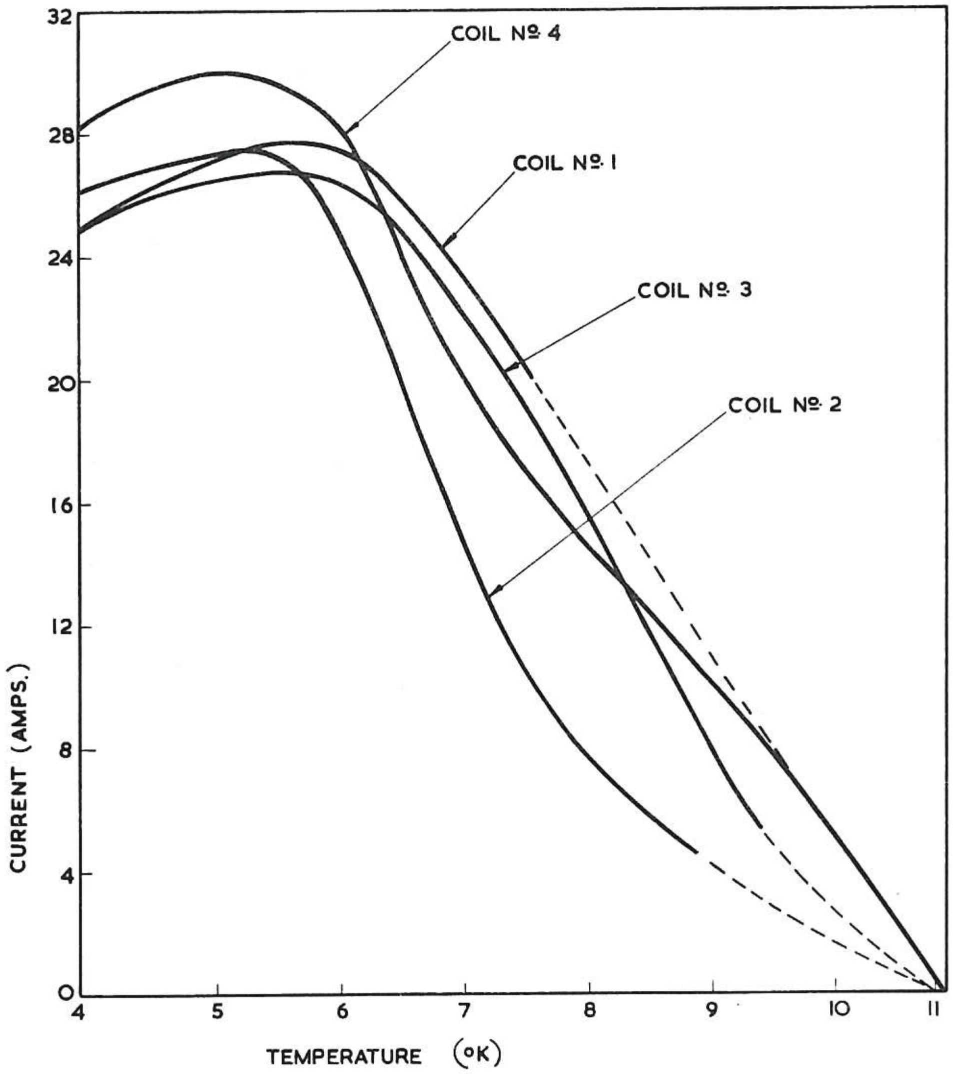
CLM-P 51 Fig. 5
Schematic diagram of charging and control circuits



CLM-P51 Fig. 6
Oscillogram of signal at quench - one pancake
Current = 26.5 Amps
Scales: Horizontal - Time 2.5 ms/cm
Vertical - Voltage Direct channel 0.10 V/cm
F.M. channel 2.8 V/cm



CLM-P51 Fig. 7
Oscillogram of signal at quench - four pancake coils
Current = 11.4 Amps
Scales: Horizontal - Time: Top 50 ms/cm
Middle 12.5 ms/cm
Bottom 1.25 ms/cm
Vertical - Voltage 2.8 V/cm



CLM-P 51 Fig. 8
Variation of quenching currents with temperature