A 70 KILOGAUSS MAGNET FOR THE PROPOSED RUTHERFORD LABORATORY 1.5 METER DIAMETER HYDROGEN BUBBLE CHAMBER

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I. INTRODUCTION

In January 1967 a design study report[1] was produced on a new hydrogen chamber for the Rutherford Laboratory. Since that date R&D funds have been made available to investigate aspects of the design which are essentially novel. The superconducting magnet is, of course, a major item in the development program, and a considerable proportion of the available effort has been concentrated upon it. Some of the results obtained have recently been reported in print.[2]

Work now being performed or already completed in connection with the superconducting magnet can best be described under four headings: selection of geometry of magnet and surrounding iron shield including proposed winding configuration; selection of stabilized superconductor; full-scale winding trials; and construction of a test magnet from full-size stabilized superconductor.

II. SELECTION OF PARAMETERS FOR THE SUPERCONDUCTOR MAGNET

The physics specification for the High Field Chamber (HFC) calls for a reasonably uniform magnetic field of 70 kG over the fiducial volume of the chamber, this being a cylindrical region 1.5 m diameter by 1 m deep. Particle beam entry across the median plane of the fiducial volume requires the field to be provided by a pair of coils separated sufficiently to allow entry channels of at least 10 cm height and 50 cm width.[3]

A general idea of the magnet-bubble chamber system can be obtained from Fig. 1. The latest dimensions of the evolving design of magnet coils are given in schematic form in Fig. 2 and the principal parameters are listed in Table I. The proposed winding configuration is shown in Fig. 3. Copper-stabilized niobium-titanium superconducting strip of dimension 50 mm by 4 or 5 mm is interwound with a cooling strip, interturn insulation and stainless steel reinforcing strips.

The cooling strip, as conceived at present, allows cooling of about 75% of one face of the conductor and is to be manufactured by spot-welding a regular pattern of stainless steel buttons of about 6 mm diameter and 1 or 2 mm thickness to a stainless steel backing strip 50 mm wide by 1 mm thick. This backing strip serves as part of the necessary reinforcement to carry hoop stresses. A sample length of cooling strip of this type is shown in Fig. 4. The economics of producing such a strip in quantity

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1. Design Study for a High Magnetic Field Hydrogen Bubble Chamber for Use on Nimrod. Rutherford Laboratory Report RHEL/S/101 (1967).
2. Progress Report for 1967 on the Research and Development Program for the High Field Bubble Chamber, Rutherford Laboratory Report AP/DS/HFC/10 (1968).
3. Proceedings of the Study Week on Optics and Beam Entry and Exit Problems for the High Field Bubble Chamber, Rutherford Laboratory Report AP/DS/HFC/9 (1967).

TABLE I

Main Parameters of Magnet Coils

Nominal central field	70 kG
Computed central field with chosen parameters (excluding contribution of surrounding iron shield)	71.4 kG
Computed peak field	80.6 kG
Total ampere turns	2.16×10^7
Inductance	11.9 H
Stored energy	3.4×10^8 J
Over-all current density	1400 A/cm^2
Operating current	7500 A
Number of single pancakes per coil	18
Number of turns per pancake	80
Thickness of pancake	50 mm
Thickness of interpancake insulation	10 mm
Thickness of each turn (including conductor, cooling strip, insulation and reinforcement strip)	9 mm

(which would involve the use of a custom-built machine) have not yet been fully investigated. Initial studies are sufficiently promising for the selection of this type of cooling strip for a test magnet now under construction.

In the HFC coils, with 75% of one face and 75% of both edges of the conductor exposed to liquid helium, full stabilization requires a heat transfer coefficient of about 0.25 W/cm^2/$^{\circ}$K. This figure is calculated on the basis of a conductor of cross section 50 mm by 5 mm, a resistivity at 80 kG of 5×10^{-8} Ω·cm and an operating current of 7500 A.

Additional interwound stainless steel strips have also been included to carry the hoop stresses generated in the coil. The total thickness of strip required (including cooling strip backing) has been determined to be 3 mm after a stress analysis of the most highly stressed pancake in the coil. A computer program which solves the differential equations for stresses in a nonhomogeneous cylindrical pancake has been devised. Since each pancake employs a multiple element winding with several strips of different material interwound (including cooling channels) the problem is treated numerically. A finite element method is used which ensures a balance of forces at each station. Nonlinear stress-strain curves can be handled allowing elastic-plastic deformation to be included. The principal stresses are tabulated as output together with the strain and displacements.

The HFC coil geometry is such that the radial stress is compressive, ensuring the validity of the above method. The dependence of radial stress on coil geometry has been discussed elsewhere.[4]

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4. A.J. Middleton and C.W. Trowbridge, Proc. 2nd Intern. Conf. Magnet Technology, Oxford, 1967, p. 140.

The results of these and other force calculations for the proposed coils are shown in Table II.

TABLE II

Stresses and Forces in HFC Coils

Maximum hoop stress in stainless steel reinforcement	21.5 kg/mm^2
Maximum hoop stress in conductor	2.93 kg/mm^2
Maximum radial (compressive) stress	0.93 kg/mm^2
Maximum axial (compressive) stress	1.80 kg/mm^2
Maximum hoop strain	0.11%
Total attractive force between pair of coils	8680 tons

Additional hoop forces which arise from differential contraction between the conductor and the stainless steel reinforcing strip on cooling from 300°K to 4°K must also be considered. Assuming that the conductor is pure copper rather than superconducting composite, the differential contraction produces a tensile stress of 2.5 kg/mm^2 in the copper (4 mm thickness) and a compressive stress of 3.3 kg/mm^2 in the stainless steel (3 mm thickness). Stresses due to differential contraction are thus much smaller than those due to current-field interaction.

The variation of hoop stress with radius in the most highly stressed pancakes in each coil is shown in Fig. 5. Only stresses due to the electromagnetic forces are included. The stress levels in both the stainless steel reinforcing strip and the conductor are a maximum at the inside edge of the coil where the peak field of 80 kG occurs and fall off as the radius increases.

It should prove possible by pre-tensioning both the copper and the stainless steel at the coil winding stage to produce a locked-in distribution of hoop stress in the windings, which, when added to that due to electromagnetic forces, results in a somewhat more uniform stress distribution across a particular pancake. The proposed coils are rather suitable for this type of treatment for the ratio of external to internal diameter is almost 2.

Surrounding the superconducting magnet, an iron shield is positioned to protect ancillary equipment from the effects of stray magnetic fields. (The shield also serves as part of the support structure for the bubble chamber itself.) An optimization of the geometry of the iron shield has been carried out so as to provide adequate shielding using a minimum weight of iron. A computer program TRIM, which originated at the Lawrence Radiation Laboratory in Berkeley, has been modified to solve this type of problem. Numerous different shapes of iron configuration have been investigated. One example is shown in Fig. 6. As might be expected with a 70 kG coil, the presence of an iron shield somewhat distant from the coils makes very little difference to the magnitude of the central magnetic field — only a few percent.

III. SELECTION OF STABILIZED SUPERCONDUCTOR

A research contract was placed in October 1967 by the Rutherford Laboratory with the one British manufacturer of co-processed niobium-titanium in copper, Imperial Metal Industries (Kynoch), Ltd. One of the objects of this contract was the development of a conductor suitable for the HFC. Numerous samples have been produced and measurements of their electrical and mechanical properties carried out. No test facility is available in the U.K. which is capable of measuring the critical current of conductors of the size required for the HFC coils. Tests have therefore been confined to samples of much smaller section and current rating, or to single filaments cut from larger samples. Fields up to 45 kG are available at the Rutherford Laboratory at present. An 80 kG 3 cm bore split pair of niobium-tin coils should become operational later this year. This new magnet will be mounted with its axis horizontal in its cryostat. Each sample under test will be aligned vertically in the 2 cm gap between the coils. With this arrangement single filaments or groups of filaments cut from full-sized conductor samples can have their critical currents measured at all fields up to 80 kG. Furthermore, the chosen arrangement permits rotation of the sample about its longitudinal axis with respect to the applied transverse magnetic field without removal of the sample from the cryostat or de-energization of the magnet. (The sample will form one straight leg of a hairpin with the return current flowing through a length of superconductor of much higher critical current, this being the other permanent leg of the hairpin.)

Anisotropy in critical current in rectangular samples of composite superconductor rolled from the round has been noted, and the extent to which this occurs in the selected samples can be speedily determined for any angle between the applied magnetic field and the wide dimension of the conductor. The evidence already existing that the relationship connecting critical current and this angle is elliptical in form will be extended or modified. The variation of anisotropy with absolute magnetic field value at fixed angular orientations will also be determined. The variation of anisotropy with field for one of the samples measured in the existing 45 kG magnet is shown in Fig. 7. An 80 kG test facility of the modest size described should allow large numbers of samples to be evaluated quickly, and could indeed be used for quality control of conductor for the bubble chamber itself.

Resistivity tests on numerous copper samples have also been carried out at $4^{\circ}K$ (without magnetic field) and these indicate that better resistance ratios can be obtained from Electrical Tough Pitch copper (ETP) than with Oxygen Free High Conductivity copper (OFHC). Consistent resistance ratios of greater than 250:1 can be obtained with ETP copper and figures as high as 600:1 have been achieved on occasion.

Facilities also exist at the Rutherford Laboratory for measuring stress-strain curves, ultimate strengths, etc. at $4^{\circ}K$ for superconducting composites, structural materials, welds and joints of various types with applied loads up to 3500 kg. An investigation of the strength of various solders has recently been completed.

It is proposed to join individual lengths of conductor to form a continuous length sufficient for the fabrication of one double pancake of the HFC coils by an explosive welding technique. This has been shown to produce joints of low resistance ($10^{-9}\ \Omega$ or less for conductor cross sections of $0.25\ cm^2$) with good mechanical strength, even after machining the joint down to exactly the same cross section as the conductor itself.

IV. COIL WINDING TRIALS

Stress calculations have shown that stainless steel reinforcement of thickness 3 mm is required to support each turn in the highly stressed regions of the coils. A number of thinner strips of the same total thickness may be preferable to a single 3 mm strip to minimize the bending stresses induced in this thick member at the coil winding stage. Furthermore, thinner strips would certainly be easier to wind into a coil.

To establish the relative difficulty of interwinding reinforcing tapes of different thicknesses, either singly or with several in parallel, into a coil of the required dimensions, full-scale winding trials have been carried out. A further object of these trials was to evaluate the practical engineering problem which would arise in coil winding, and to determine winding tensions, etc.

A standard motorized turntable, 8 ft square, from an Asquith Boring Machine, was temporarily converted to a coil winding machine. A general view of the winding jigs and fixtures around the winding table is shown in Fig. 8. Three 50 mm by 1 mm stainless tapes are shown being interwound with 50 mm by 5 mm annealed copper. In this final winding test 18 composite turns were added, free ends were then secured, and the resulting coil was removed from the machine. Figure 9 shows the completed coil of 18 turns.

In earlier winding operations 0.5 mm, 1 mm and 3 mm thick steel tapes were tried in various formations. No cooling strip was available and no interturn insulation was incorporated. For simplicity, winding tensions were applied by squeezing the conductor or reinforcement strip between "Tufnol" blocks with a known force and reliance placed on friction to produce a constant tension. More sophisticated tensioning systems will probably be required for the final coils.

The minimum tension required to produce a tightly wound coil was determined for the different strips, and this varied between about 20 kg for the 0.5 mm thick steel tape (0.8 kg/mm^2) to 150 kg for both the 3 mm thick steel and 5 mm thick copper (1 kg/mm^2 and 0.6 kg/mm^2). In some tests tensions were increased to the equivalent of 4 kg/mm^2 without noticeable change in the tightness of wind. The final thickness of each coil was compared with the value calculated from the known individual strip thicknesses. The difference in corresponding figures never exceeded 3%. As it was not possible to slide a fine feeler gauge between turns, it is concluded that this 3% additional build-up was due to known factors such as edge burrs on the stainless steel tapes, etc.

The general conclusion from the winding trials is that little difficulty should be experienced in winding conductors and steel support strips of the required thickness at the required diameters. Indeed, the whole winding operation proved much easier than had been anticipated.

V. RACOON TEST COIL

A test magnet made from full-size bubble chamber conductor is at present under construction. Coil winding should be completed in September of this year. This magnet, code named RACOON, uses approximately the same winding configuration as the HFC magnet, and will thus be used to check the performance of the selected stabilized superconductor in a thermal and magnetic environment similar to that which will prevail in the large coils. This test coil, being for experimental use only, need not be built with such a high safety margin on stability. Indeed the prime purpose in building such a coil is to determine quantitatively the stability margin of the proposed design of the large coils.

The conductor specified for RACOON is to carry 7500 A at 80 kG — the same as the HFC coils. Conductor dimensions have been chosen at 50 mm by 3 mm to be less conservative than the HFC coils (50 mm by 4 or 5 mm). A cooling channel thickness of 1.5 mm has been adopted (cf. HFC coils 1 to 2 mm thickness). Because of the small diameter of the test magnet, no stainless steel reinforcement of the coils other than that provided by the cooling strip itself is required. The over-all current density for RACOON is 2600 A/cm^2, almost twice that of the HFC magnet (1400 A/cm^2).

The principal dimensions of RACOON are given in Fig. 10. The magnet comprises six double pancake coils. Initially all these double pancakes will be identical in construction, but it is envisaged that additional double pancakes will be manufactured and substituted at a later stage. These special pancakes will test different conductors or winding configurations or perhaps have many explosively welded conductor joints, etc.

At the specified operation current the RACOON coil alone will provide a central field at 26 kG and a peak field of 27 kG. Since the conductor is rated at 7500 A at 80 kG, it should also be capable of carrying more than 15 000 A at 50 kG. It is thus proposed to provide a 15 000 A power supply to energize RACOON to fields up to 52 kG. At this upper limit, the magnet will be only partially stabilized (about 1 W/cm^2) so that it should prove possible to study the effect of flux jumps in wide conductors under somewhat extreme conditions. The main parameters of RACOON are given in Table III.

The dimensions of the RACOON coil have been carefully selected so that it can operate as an insert coil to the CERN test facility BRARACOURCIX. Under these conditions, with normal operating currents in both BRARACOURCIX and RACOON, peak fields of over 80 kG should be achieved. It is hoped to arrange such a joint test late this year or in early 1969. (In Fig. 10, the outer chain-dotted regions represent the BRARACOURCIX coils.)

If all this proves possible, the RACOON coil will have duplicated the thermal and magnetic environment to be expected in all regions of the proposed HFC coils.

TABLE III

Main Parameters of RACOON Coil

Internal diameter of windings	135 mm
External diameter of windings	304 mm
Length of coil	655 mm
Number of double pancakes	6
Number of turns per pancake	16
Total number of turns	192
Specified conductor current at 80 kG	7500 A
Magnetic field produced by coil	
1. With 7500 A excitation	
Central field	26 kG
Peak field	27 kG
Over-all current density in windings	2640 A/cm^2
2. With 15 000 A excitation	
Central field	52 kG
Peak field	54 kG
Over-all current density in windings	5280 A/cm^2
3. With 7500 A excitation as an insert in BRARACOURCIX (1000 A)	
Central field	~ 84 kG
Peak field	~ 85 kG

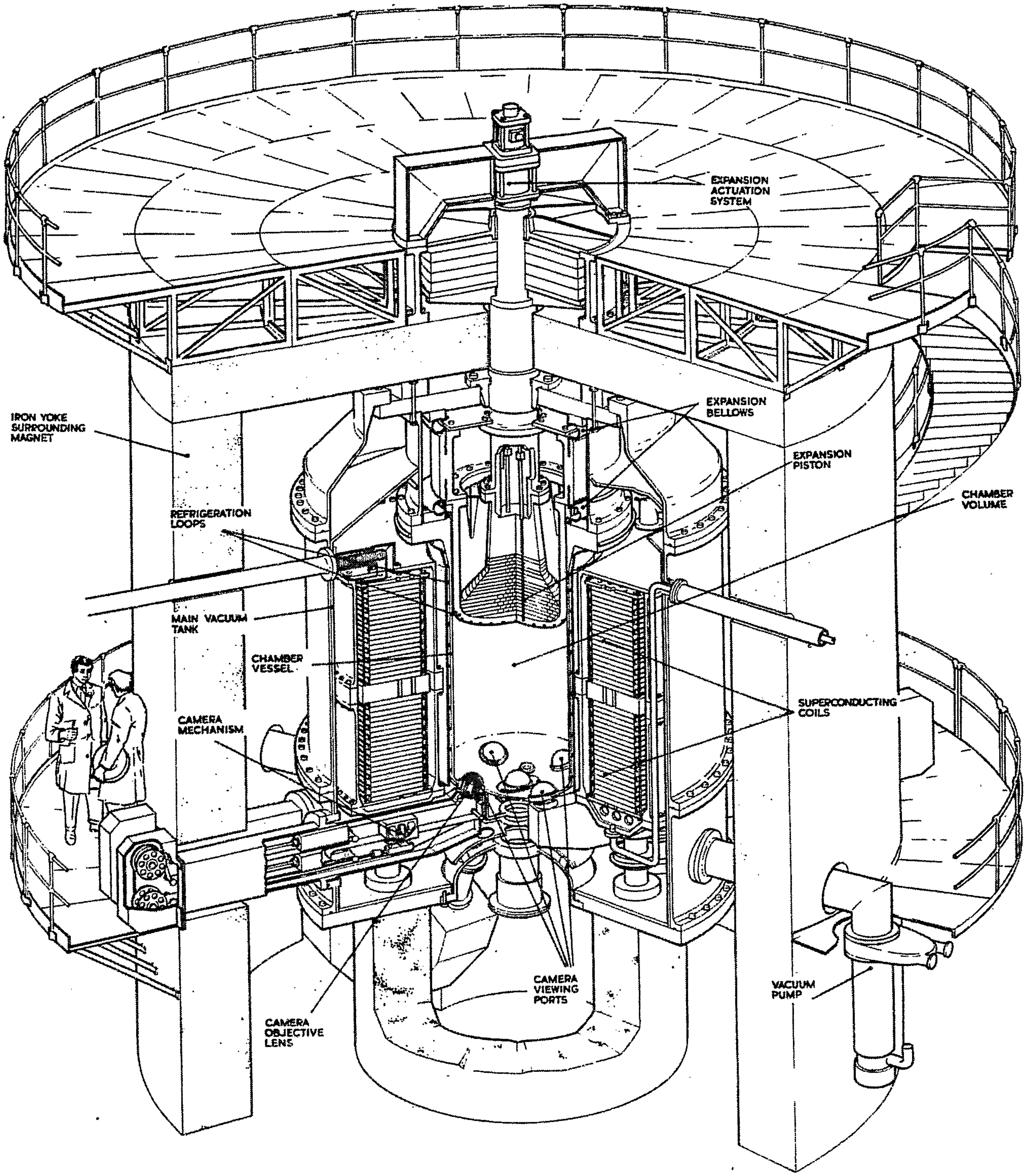

Fig. 1. Artist's impression of proposed High Field Chamber.

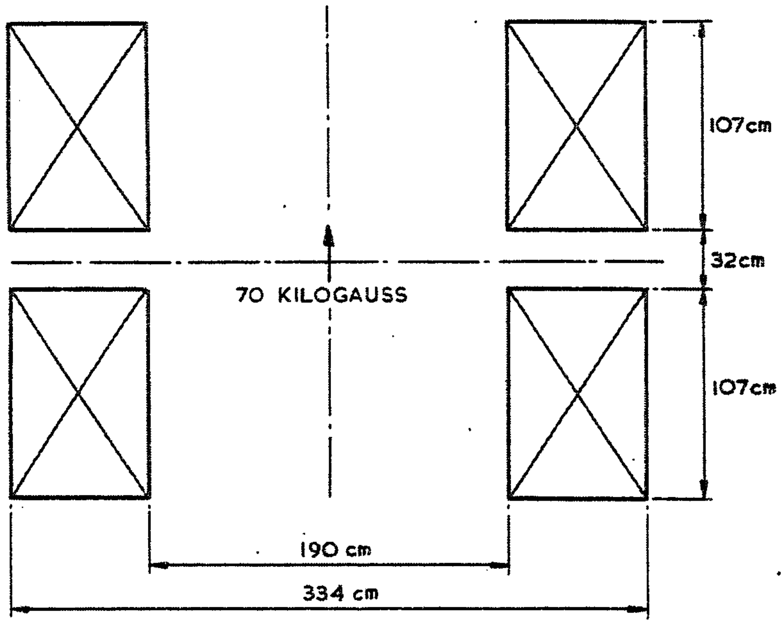

Fig. 2. Principal dimensions of High Field Bubble Chamber magnet coils.

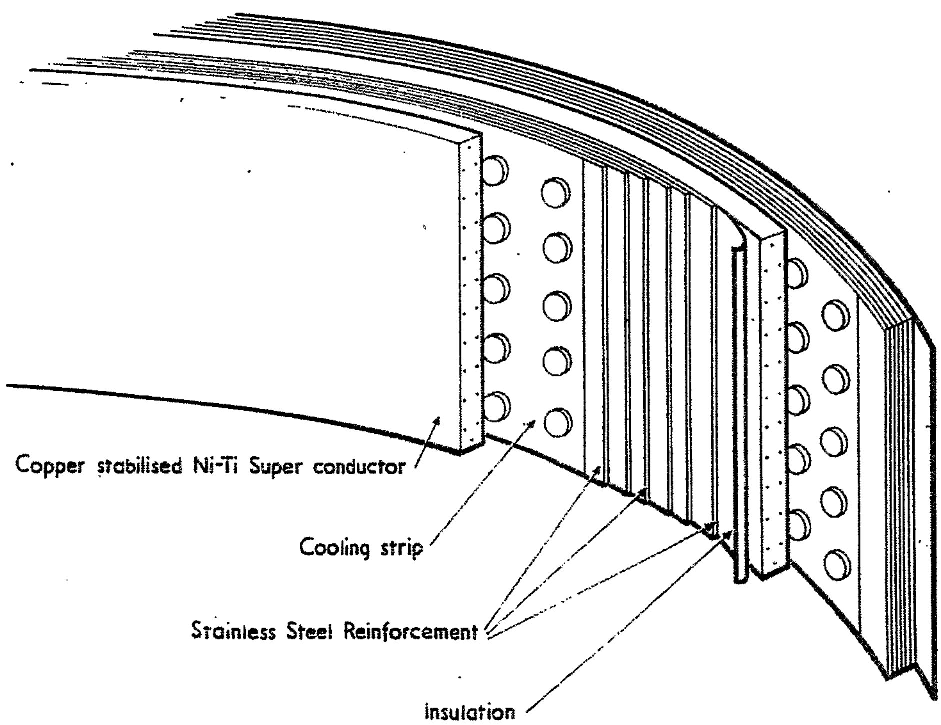

Fig. 3. Proposed winding configurations for superconducting coils of High Field Bubble Chamber.

Conductor	50 mm x 4 or 5 mm
Cooling channels	50 mm x 2 or 1 mm (75% of one conductor face exposed)
Stainless-steel reinforcement	50 mm x 3 mm total thickness
Insulation	50 mm x 0.2 mm

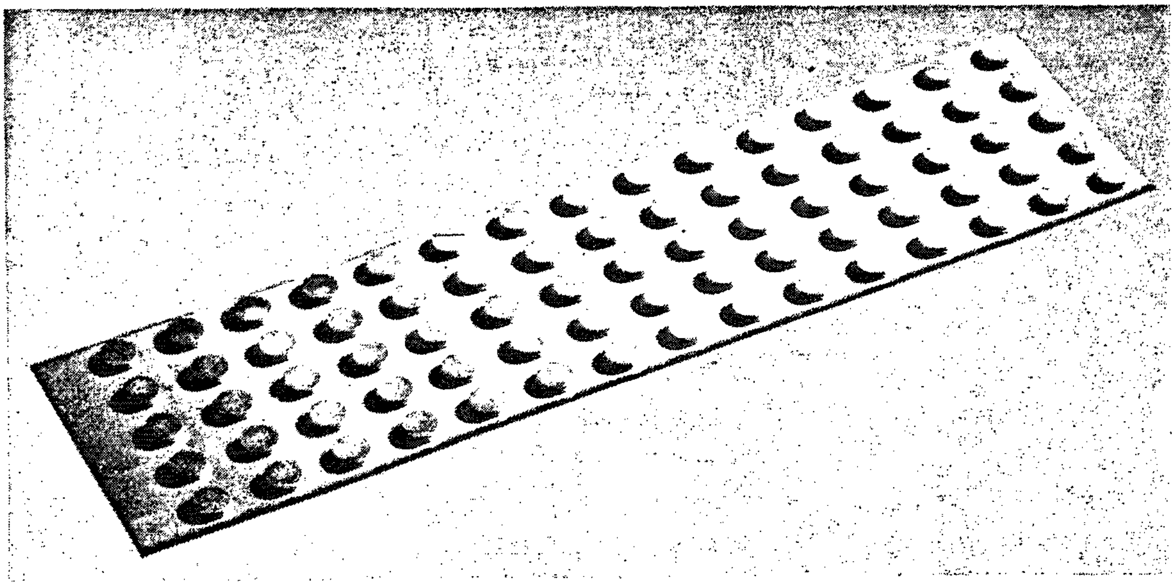

Fig. 4. Stainless-steel cooling strip.

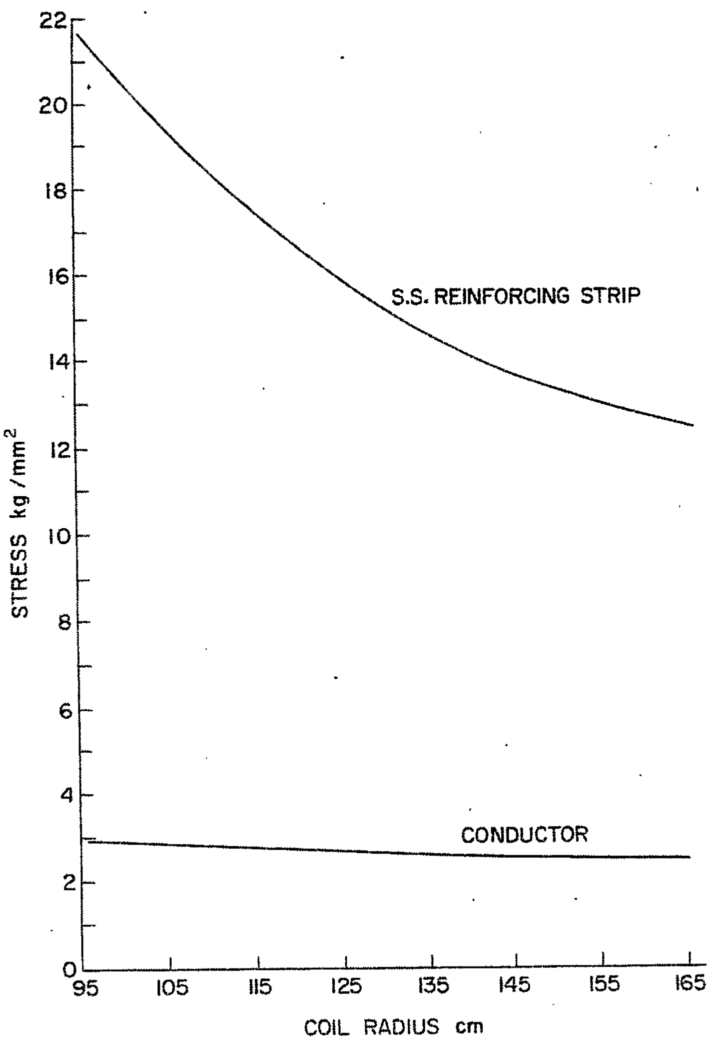

Fig. 5. Hoop stresses vs coil radius for most highly stressed pancake in HFC coil.

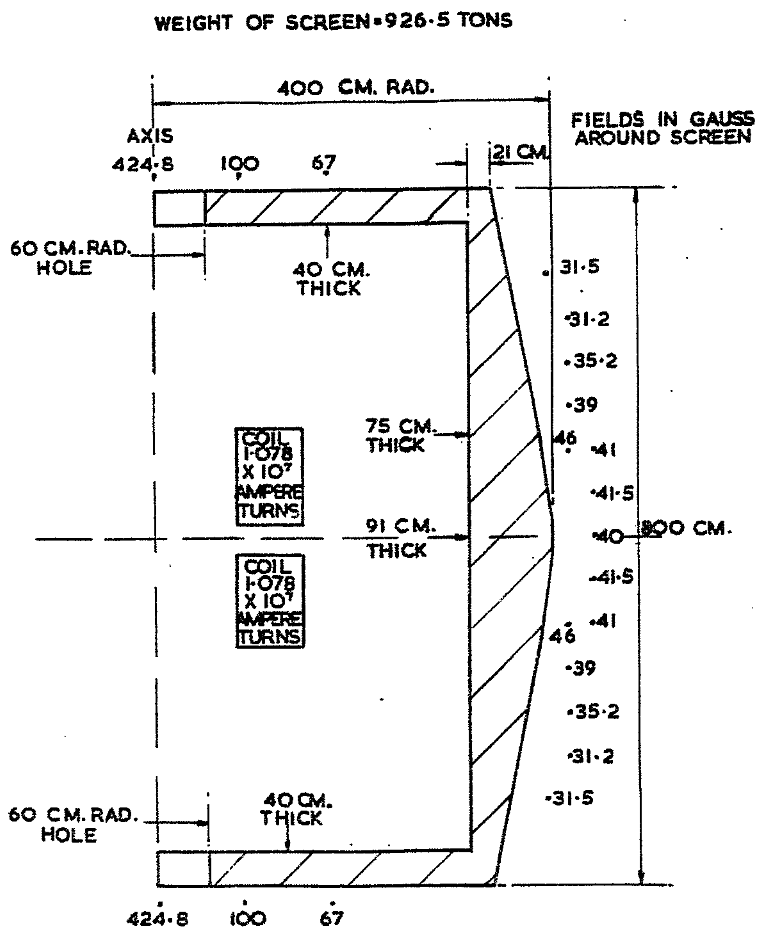

Fig. 6. High Field Bubble Chamber screen No. 5A.

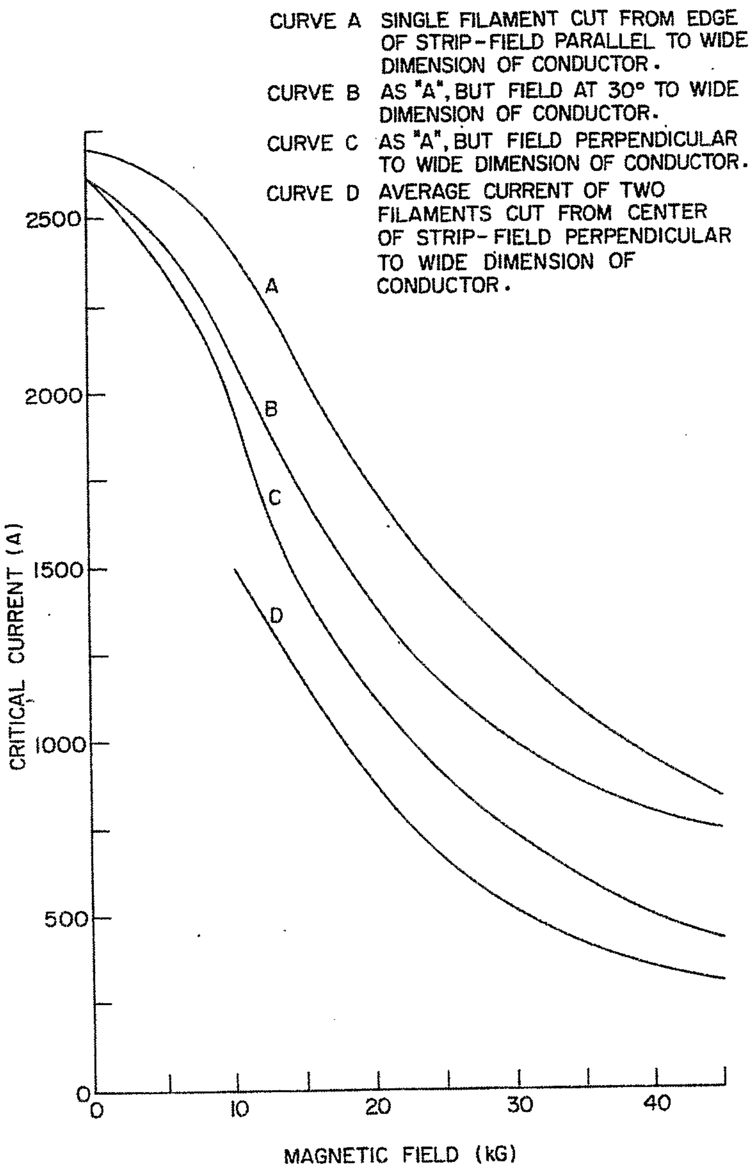

Fig. 7. Anisotropy test of I.M.I. Niomax-M sample BC4/1D.

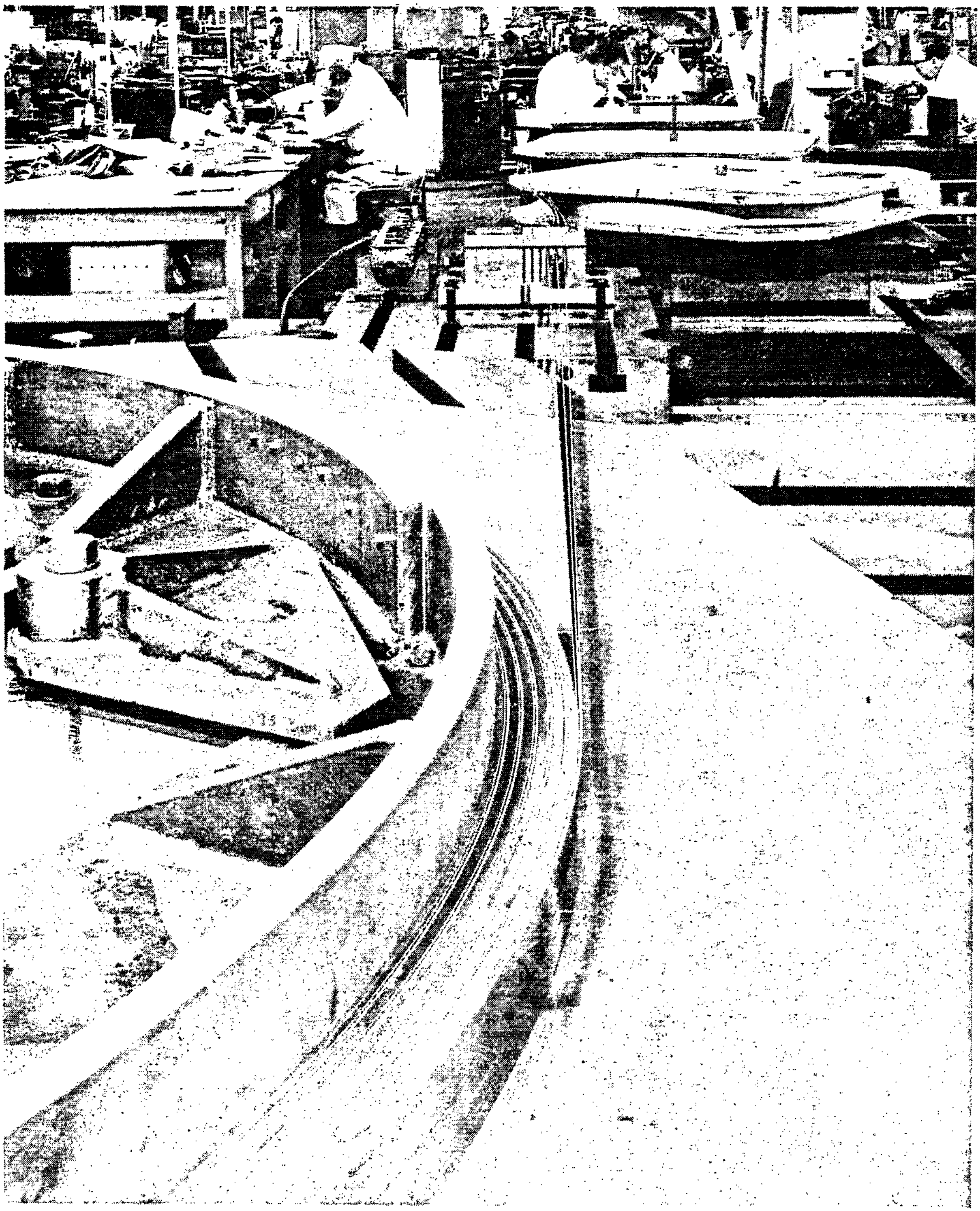

Fig. 8. Testing winding of full-scale single pancake.

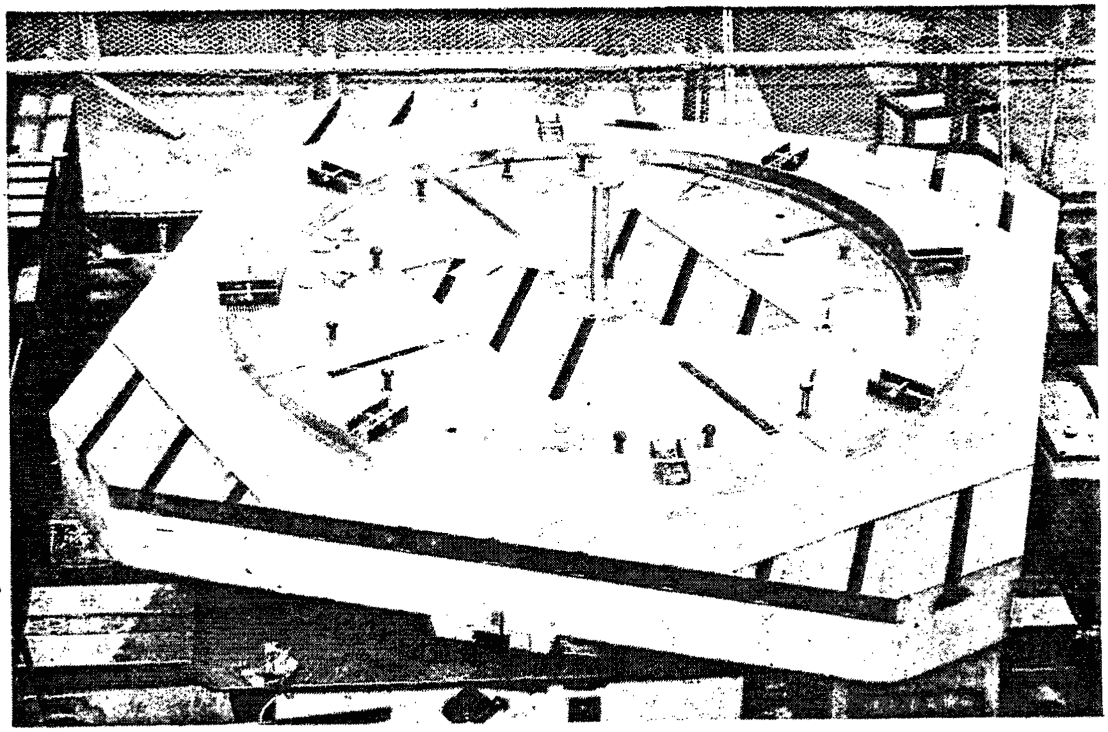

Fig. 9. Completed test pancake.

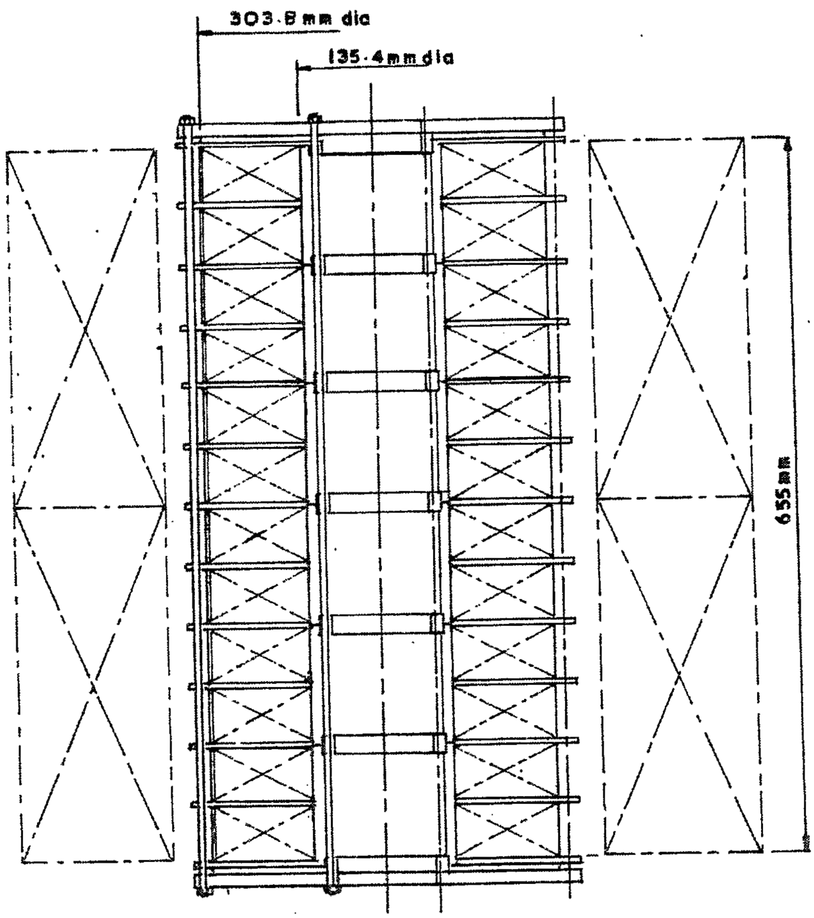

Fig. 10. Cross section of RACOON coil.