SUPERCONDUCTING PULSED MAGNETS FOR A 1000 GeV SYNCHROTRON

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Abstract

In this paper the experimental work in progress at the Rutherford Laboratory on superconducting pulsed magnets for synchrotron application is reported. The present state-of-the-art is described, in particular the recent preliminary testing of the first superconducting dipole of representative aperture. Future plans include the construction and testing of a fully engineered version of this magnet, representative in all respects except one (length) of that required for a 1000 GeV conversion of the European 300 GeV machine. This magnet is scheduled for completion in 1973.

1. Introduction

A programme of theoretical and experimental work to prove the technical feasibility of a superconducting synchrotron has been in progress at the Rutherford Laboratory since about 1965 1,2). The early experimental work on conductors culminated in the development in 1968/9 of special filamentary superconductors 3) for pulsed magnet operation and the subsequent construction of solenoids and dipole magnets to test these materials. Recently a dipole magnet of 10 cm aperture has been successfully tested and is reported on in this paper.

In the last year a new focus for this work has arisen with the approval of the 300 GeV project and the suggestion that it should be uprated to 1000 GeV using superconducting magnets 4). Prototype magnets now under design at the Rutherford Laboratory are in consequence based on parameters (such as field uniformity criteria) derived from preliminary machine design studies of superconducting conversion schemes for this machine. Furthermore to ensure that these magnets are as representative as possible of those which will be required for the synchrotron itself, it has become necessary to undertake design studies of helium refrigerators, cryogenic distribution systems and magnet power supplies since all these could profoundly influence the final design of magnet. These studies, now well in progress, are also directed exclusively at the various superconducting conversion options offered by the 300 GeV machine.

Work towards superconducting synchrotrons is becoming increasingly organised on a European scale through the GESSS Collaboration (Group for European Superconducting Synchrotron Studies) with IEKP/Karlsruhe, CEN/Saclay and Rutherford Laboratory actively engaged in complementary development programmes.

In this paper some of the more important aspects of the work of the Superconducting Applications Group at Rutherford Laboratory are described.

2. Present Status - Magnet Development

Construction of a 10 cm aperture, 40 cm long dipole magnet has recently been completed, and testing has commenced. This magnet, code-named AC3, was conceived as a test-bed for a substantial quantity of the newly-developed superconducting stranded cables and as a means of verifying experimentally the theoretical predictions for "ac losses" in such conductors. For this latter reason as little metal as possible was used both in the construction of the force restraining structures surrounding the coils and elsewhere to ensure that dynamic heating during magnet pulsing could be attributed unambiguously to "ac losses" in the conductor rather than to a mixture of these losses and eddy current heating in adjacent metal parts.

The AC3 magnet comprises six double-layer coils, three per pole. Each of these sub-units has a semi-annular cross-section with sector windings along its length and ends wound in the vertical plane. In Fig. 1 a mock-up cross-section illustrates the type of construction used for the sub-units. The size of the vertical end windings can be deduced from Fig. 2 which shows one end of the assembled coil. The conductor is a transposed cable compacted to 5 mm square and consisting of 90 strands of composite superconductor and 13 strands of pure copper. Each 0.4 mm diameter strand has 1045 niobium-titanium filaments each 8μm in diameter embedded in a cupro-nickel and copper matrix. The conductor twist pitch is 3.6 mm. Each strand is individually insulated with a 'Pyre ML' enamel coating and the entire cable has a 'Terylene' covering woven over it. Each double layer sub-unit has two cooling mats made up of parallel individually insulated copper wires positioned such that there is one mat between each layer of windings in the assembled coil. The cooling mats emerge into channels along the magnet length allowing them direct contact with liquid helium. Each sub-unit is separately vacuum impregnated with an Epoxy-Adiprene resin mixture. Regions in the mould not occupied by windings are filled wherever possible prior to impregnation with alumina granules in an attempt to produce a moulding with uniform thermal contraction properties. Without loading the resin in this way there would be danger of some cracking taking place on cooling to liquid helium temperatures or more importantly during operation of the coil. The normal operating

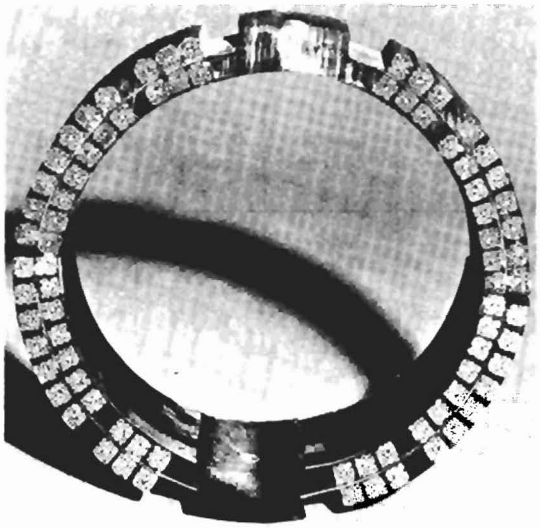


Fig. 1 Sector Geometry Winding Configuration of Type used in AC3

Fig. 2 Arrangement of Vertical End Windings in AC3

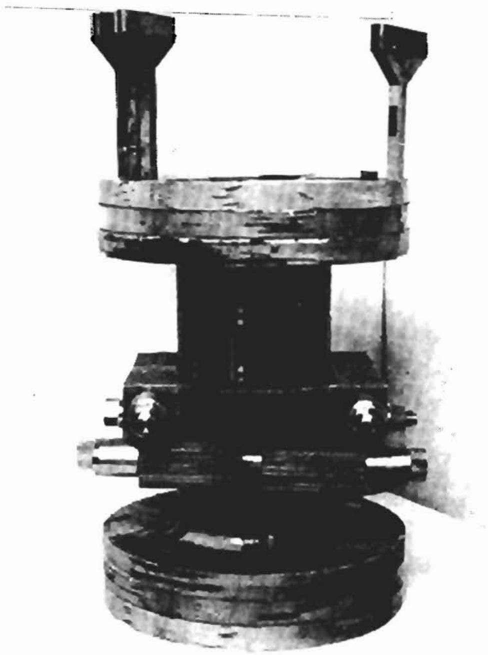


Fig. 3 Assembled AC3 Windings with some of the Force Restraining Clamps in Position

current of the cable is 5000A at 4T. In the assembled magnet this current level has not yet quite been achieved and there are indications that one or more of the individual strands in the cable might have been damaged or even broken during the compacting operation.

In the force restraining structure surrounding the coils epoxy-bonded fibre-glass laminate is extensively used to contain the bursting forces (see Fig. 3). Although such a material with its low Young's Modulus is far from ideal for this purpose it was chosen, as already stated, to permit accurate "ac loss" measurements to be performed. Alternative force restraining structures would involve laminated and individually insulated components (such as will certainly be required for final synchrotron magnets) but for a laboratory magnet such as AC3 these were not considered appropriate. The trouble free operation of AC3 on its first test run has supported the choice but no measurements have yet been made of shape distortions of the windings under the forces generated during pulsing.

Again because of the experimental nature of AC3, no custom-built cryostat has been constructed for it. Testing has been carried out with the magnet aligned vertically in a standard 50 cm laboratory cryostat (see Fig. 4).

As a preliminary to testing the entire magnet, a number of the six separate sub-units were tested either singly or in a group of three. No 'training' was observed when a single sub-unit was tested. ('Training' describes the situation in which premature quenching of a coil occurs well below its expected critical current on its first energisation. Gradually improving performance is noted after each subsequent energisation and quench. Finally a repeatable quench current is achieved and reliable magnet operation can take place with a good safety margin at perhaps 80% or 90% of this value. 'Training' as observed in resin impregnated coils is believed to be due to local cracking in the resin with the release of locked-in mechanical energy built up by differential contraction on cooling to 4°K).

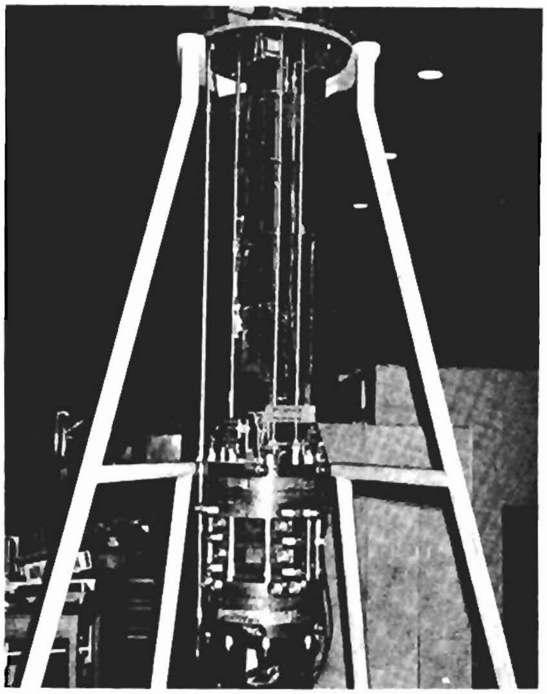


Fig. 4 General View of AC3 showing Current Leads and Cryostat Top Plate

Table 1 - Quenching currents of AC3 dipole magnet on first test run (September 1971)

Current rise time S	Observed quench current A	Central field at quench T	Peak field at quench T
100	4900	3.75	4.25
2	4800	3.65	4.15
1	4800	3.65	4.15
0.5	3850	2.95	3.50

Table 2 - Measured and Predicted "ac losses" for AC3 dipole magnet

Current rise time S	Peak Operating current A	Measured loss W	Calculated loss W
2	4000	9	11
1	4000	22	21

In the testing of the assembled magnet some 'training' was observed, a quench occurring at 3900A on the first energisation. (The absence of 'training' on single windings suggests that relative movement of one coil sub-unit with respect to another rather than wire movements or cracking in a single sub-unit is the cause.) After about 20 quenches a current of over 4800A could be consistently achieved for slow rates of current rise. Under pulsed operation the observed quench currents were as given in Table 1. A continuous series of current pulses of triangular waveform and uniform duration were applied to the magnet. Starting at a low peak current value the amplitude of the sawtooth waveform was gradually increased over a number of cycles until a quench was recorded.

The results of these tests indicate that in a magnet with good internal cooling arrangements satisfactory operation under pulsed conditions with current rise times in the 1 to 2s range can be achieved at current levels only marginally less than the critical current of the conductor. At a 0.5s rise time - AC3 was designed for a 1 to 2s rise time - the expected loss in performance is attributed to a rise in coil temperature of almost 1°K under severe "ac loss" heating and consequent reduction in the critical current of the conductor. It should in addition be noted that the triangular current waveform as applied during the tests produces more dynamic heating in the magnet per unit time than would the usual synchrotron current waveform with its extended 'flat top' since the superconductor is genuinely lossless during 'flat-top' operation.

During testing of AC3 measurements were made of "ac losses" with 1 and 2s current rise time. The increase in helium boil-off when the coil was being continuously pulsed to a constant peak current compared with that with the coil quiescent was measured thus allowing the dynamic heat load of the coil to be determined. The results are given in Table 2. Good agreement is shown between these measurements and the predicted losses in the conductor (filament, self field and eddy current losses) calculated on the basis of the known filament diameter and known matrix configuration and composition.

To date AC3 has been pulsed about 1500 times and has been quenched 36 times. The energy stored in the magnet at peak current is 60 kJ. Approximately 50% of this is extracted by a protection system following a quench. The testing programme is continuing.

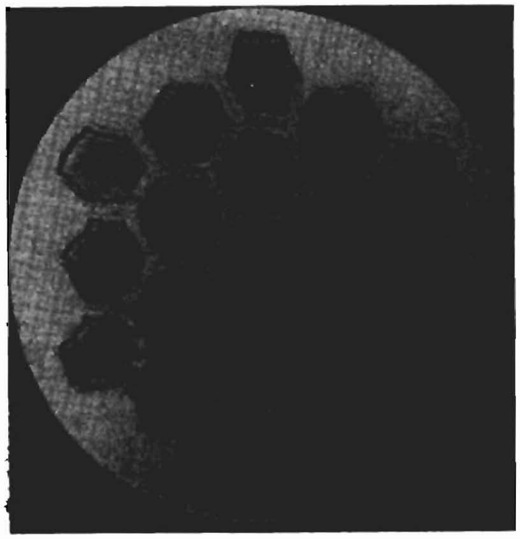
3. Present Status and Future Problems - Conductor Development

That superconducting cables suitable for prototype pulsed synchrotron magnets can be manufactured is now an established fact. Further developments in composite niobium-titanium conductors can therefore be aimed at increasing the overall current density in a cable, reducing the "ac losses" during pulsed operation and simplifying the design and production processes wherever possible to reduce costs. These three aims are closely interconnected with the second and third being to some extent in opposition.

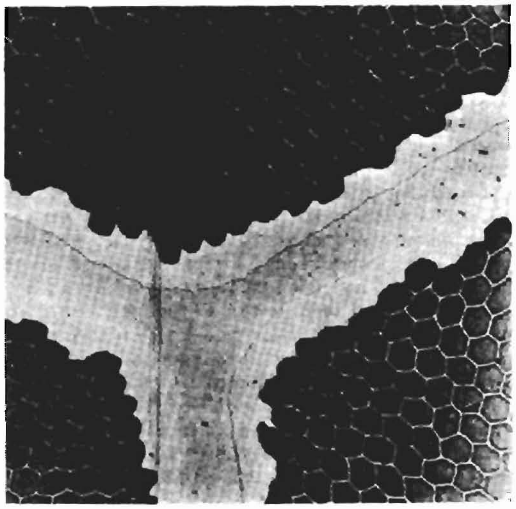
Niobium-titanium alloys in the fine filamentary form are available commercially with guaranteed current densities of over 1000A/mm^2 at 5T and at 4.6°K (the likely operating temperature of a superconducting synchrotron). Since the niobium-titanium in a typical conductor for pulsed magnets comprises only about 40% of the cross-sectional area - 60% is copper and cupronickel - and since cabling and compaction produces only a 50-75% filling factor this reduces the overall current density in a cable to 200-300A/mm^2. (Interturn and interlayer insulation and cooling mats or helium cooling channels in the magnet coils further reduce this figure by perhaps 20%.) Considerable scope therefore exists for increasing the niobium-titanium content of the composite wires if this can be done without prejudicing their intrinsic stability in operation. Experimental work on cables has shown that filling factors towards the top end of the quoted range (and perhaps beyond) can be obtained more easily in cables with small numbers of individual strands.

The question of "ac losses" in synchrotron magnets cannot strictly be considered in isolation from the question of static heat loads in cryostats, transfer lines and other components of the liquid helium distribution system. Presumably in an ideally optimised superconducting synchrotron the dynamic losses set by the conductor design would be approximately equal to the static heat inleaks set by the available insulation techniques. At the present time insufficient study of the cryogenic distribution system of a superconducting synchrotron has been undertaken to give reliable estimates of these static loads. The present indications are that the dynamic losses of existing conductors scaled to the quantity required for a synchrotron exceed the estimated static losses by a factor of between 2 and 4. Since the "ac losses" in the latest three-component conductors are dominated by the losses in the filaments themselves there are good reasons why filaments finer than the 5-10µm presently available should be produced if the metallurgy allows this.

The question of conductor design and production processes is something that must be left largely to the conductor manufacturers. The possibility that the sophisticated low-loss conductors presently under development could be rejected on economic grounds in favour of higher loss, cheaper conductors and larger refrigeration plant should not be ruled out altogether at this stage.



a)



b)

Fig. 5 a) Experimental 7600 Filament Superconducting Composite.

b) Enlarged view of Section of this Composite.
Manufacturer: Imperial Metal Industries (Kynoch) Ltd.

The trends in conductor research mentioned above are used in general to guide the work performed by Imperial Metal Industries Ltd under contract to the Rutherford Laboratory. Composites with as many as 8000 individual filaments on a copper/cupro-nickel matrix have been produced

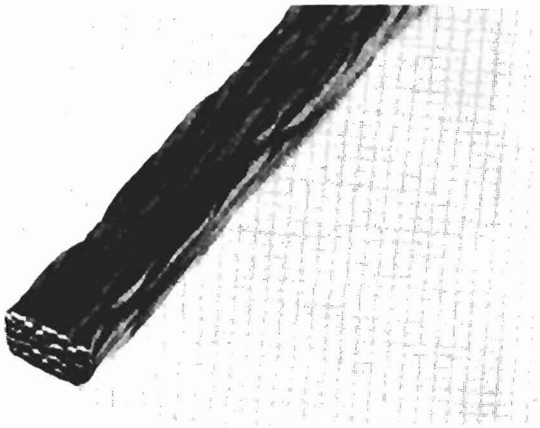


Fig. 6 Compacted cable produced at Rutherford Laboratory from 25 strands of Composite Superconductor

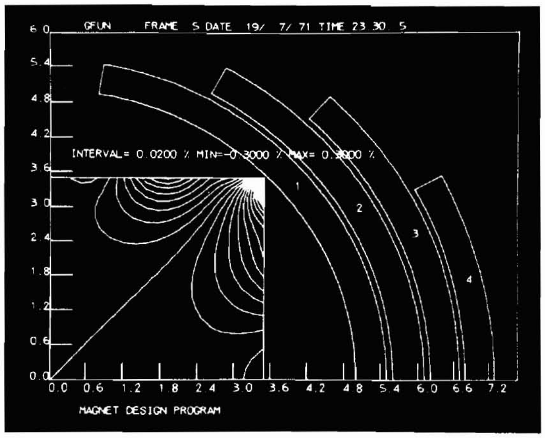


Fig. 7 Field homogeneity contours for dipole magnet. The computer program automatically adjusts the lengths of the current bars 1-4 to optimise field homogeneity.

in experimental quantities. In Fig. 5 a 7600 filament conductor with 19 groups of 400 filaments separated by cupro-nickel and embedded in a copper matrix is shown. Assuming that such a conductor is processed down until 5 μm filaments are achieved and that the current density in the filaments is 1250 A/mm^2 at 5T and 4.6°K, then a transposed cable of 32 strands is required to carry 5000A with a 20% safety factor. There are however unanswered questions regarding the stability of such conductors. With strand diameters approaching 0.7 mm unequal current sharing between the outer and inner filaments could reduce stability and increase self-field losses. A full experimental investigation of this problem is in hand. If the conductor is shown to possess sufficient stability, a cable of the type described will be considered for use in the prototype magnets outlined in the next section. In Fig. 6 is shown a 25 strand version of such a cable.

4. Future Plans - Magnet Prototypes

Two further prototype dipole magnets (AC4 and AC5) are currently under design. The timescale for the construction and testing of these magnets is set by the 1974 date in the 300 GeV programme at which time the first decision on the superconducting option as a means of converting the accelerator to higher energies has to be made. The aim at Rutherford Laboratory is thus to construct and test by this date a fully engineered dipole magnet representative in all respects except one, length, of that required for a 1000 GeV superconducting conversion scheme. This magnet (AC5) should be completed by the middle of 1973 and life-tested for upwards of a million pulses by the end of that year. A pre-prototype magnet AC4 is currently being built to evaluate some of the engineering problems which must be solved in AC5.

In conception, AC5 differs from the already tested AC3 in a number of important ways. It will have

a) a higher operating magnetic field, 4.5T. (AC3 has to date produced 3.8T at quench and could therefore be operated satisfactorily at perhaps 3.0 to 3.3T.)

b) A magnetic field uniform to 1 part in 10^3 over 80% of the 9 cm diameter aperture. (No such field uniformity constraint was placed on the design of AC3.)

c) An iron yoke operating at 4°K. (AC3 has no yoke but if one were fitted 4.5T could be achieved.)

d) A more advanced conductor with perhaps 25 or 30 strands of composite with 7600 Nb-Ti 5μm filaments. (AC3 cable has 90 strands of composite with 1045 Nb-Ti 8μm filaments.)

e) A more production-oriented engineering approach to the design.

To achieve the stated accuracy requires in the first instance careful computation of field shapes for optimised conductor configurations. These configurations must also lend themselves to being readily engineered. The presence of an iron yoke close to the windings and possible saturation effects increases the complexity of the computation. To reduce the human effort involved in these calculations, direct graphical output of computed field shapes is now available as standard. Facilities are also available for on-line operation of the computer so that variations in parameters such as for example conductor position can be made direct from a typewriter keyboard and immediate display of the resulting field shapes implemented 5). Some examples of the output obtained with this on-line system are shown in Figs. 7 and 8. (The layout scheme for conductors and iron yoke as illustrated has been adopted for AC4 with some dimensional changes.) The internationally-used program TRIM which is based on finite element methods and which allows permeability variations with field in the iron to be taken into account has also been adapted for output displays on the graphics terminal.

The whole engineering approach to the design of AC5 is rather different to that used for AC3. Although it would be premature to claim at this time that all the basic problems of pulsed synchrotron magnets have been overcome, it is nevertheless not too soon to consider the problems of producing such magnets in quantity. The design of AC5 reflects this sort of thinking. Although AC5 will be only about 1 m long, only techniques which could readily be used in a 7 m long version of this magnet will be adopted for its construction. Preliminary consideration is also being given to the construction of a pulsed quadrupole magnet which will use the technology being developed for AC5. This will be built on much the same timescale as AC5 if future resources allow.

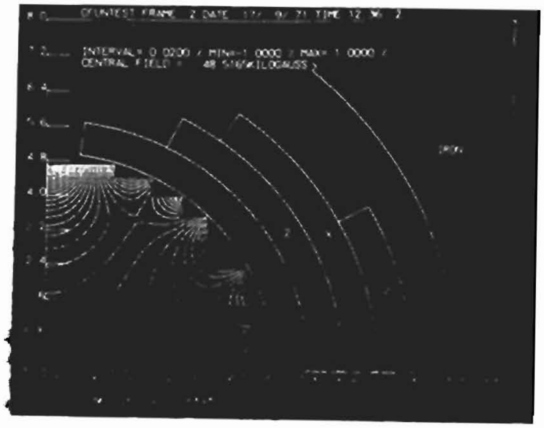


Fig. 8 Central Region of iron clad Dipole Magnet showing field homogeneity in the Beam Aperture. The central field is 4.85T and contours of 0.02% homogeneity are drawn. The aperture is 10 cm diameter. The current density in the windings (numbered 1 to 4) is 180 A/cm^2. The nearly cylindrical boundaries of the iron shield are located at 9 cm and 23 cm radius. The iron contributes 30% of the total field.

References

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DISCUSSION

J.A. MARTIN: How does the observed value of 4900 A maximum compare with the short-sample DC-characteristics of the cable?

D.B. THOMAS: The value of 4900 A is more than 90% of short sample assuming that none of the 90 strands is broken. The indications are, however, that several strands have been broken during compaction.

E. HAEBEL: Do the measured loss figures you quoted include the heat input through the current leads?

D.B. THOMAS: Allowance has been made for the extra current lead load in the quoted figures.

J.P. BLEWETT: What will be the diameter of the 7600 filament wire?

D.B. THOMAS: Approximately 0.7 mm diameter if the filaments have 5 μm diameter.

G. BRONCA: The figure you gave about the current density concerns the conductor itself (25 kA/cm^2). What is the overall average current density in the coil.

D.B. THOMAS: The 5000 A cable is 5 mm x 5 mm, so the current density is 20 kA/cm^2. The overall current density in the windings is about 18 kA/cm^2 (at 4T).

P.F. SMITH: The degree of compaction achieved in this 90-strand cable was only about 50%. In improved cables for future magnets, we can achieve compactions of 70% or more, and should thus be able to reach more than 25 kA/cm^2 in the coil cross section at 45 - 50 kG.