SUPERCONDUCTING SYNCHROTRON MAGNETS - PRESENT STATUS

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Introduction

This paper reviews the progress which has been made, and the problems which still remain, in the development of pulsed superconducting synchrotron magnets.

The main preoccupation in this field of work for the past 4 years has been the development of suitable stable, low loss, conductors. During the past 18 months, however, very substantial progress has also been made in the understanding of problems associated with coil design, fabrication, and performance, to the extent there now appears to be no significant obstacle to the production of satisfactory prototype synchrotron magnets.

It is also of importance to note that much of this work is directly relevant to the alternative (and rather simpler) problem of producing high field dc superconducting storage ring magnets.

This paper is in three parts :

1) We begin with a brief reminder of the principal problems and design constraints, together with their practical or economic origins.

2) We discuss the present state of knowledge, and future outlook, for each of the problems listed in (1).

3) We summarise progress and future plans for complete magnet prototypes, incorporating the various ideas discussed in (2).

The object is to present a fairly complete general picture of the subject, and an up-to-date indication of world progress, but not to give detailed results or attempt a comparative survey of the development programmes of different laboratories.

1. Problems and design constraints

Work on superconducting magnets has now been in progress for over ten years; the problems of producing dc fields up to, say, 60-70 kG are reasonably well understood, and from a purely technical view point it would be relatively straight-forward to extend the technology to allow the magnet field to be cycled between zero and maximum with a few seconds rise time.

However, the objective is not only to be able to produce a high field pulsed synchrotron magnet, but to do so with an accuracy, reliability, and overall cost/GeV comparable with (or better than) the conventional 10-20 kG magnet systems

It has been shown many times1) that this is possible in principle, provided that certain rather severe design constraints can be met. The most important of these are as follows :

1.1 Refrigeration cost. In order to reduce refrigeration requirements to an acceptable level, the mean superconductor ac loss must be restricted to about 10-20 watts per metre length of magnet. For a reasonable magnet cycle time (e.g.10-20 sec), this has necessitated the development of twisted multifilament superconducting composites, with filament diameters in the region 5-10 μm, and with stringent criteria relating to twist pitch and interfilament resistance[3]. To achieve the typical 2-5000A operating current requirement, these composite wires have then to be formed into fully transposed multistrand braids or cables, which must be mechanically compacted to obtain a satisfactory packing factor, but without significantly affecting the superconductor performance during this process.

A further consequence of the ac heating is the necessity to minimise the difference ΔT between the maximum temperature within the magnet and the temperature of the refrigerant. Because of the rather rapid fall in critical current with increasing temperature and the rapid increase in refrigeration cost with decreasing temperature, the difference ΔT should be kept certainly below 0.2°K and preferably below 0.1°K, particularly since a further significant temperature difference will probably occur in the main refrigeration distribution system.

1.2 Superconductor and power supply costs. Both of these depend on the size of the magnet, (the former depending on the volume of material and the latter depending, via the stored energy, on the volume of magnetic field). To achieve acceptable values necessitates firstly an aperture radius of order 5 cm or less, and secondly a mean current density in the region 25-30,000 A/cm^2 or higher in order to reduce the coil thickness (at $\sim$ 50 kG) to 3-4 cm or less. A somewhat lower current density, $\sim$ 20,000 A/cm^2, is acceptable when a low temperature iron shield is used, since the latter will itself contribute typically 25-50% to the field.

However, despite the high current density in the superconductor itself ($> 10^5$ A/cm^2 at 50 kG), the above values are not easy to achieve after the appropriate dilution factors have been included for the composite matrix, cabling, insulation, cooling channels, and operating margins allowed for coil peak field, the above mentioned temperature rise ΔT, and any current degradation mechanisms. In consequence it is necessary to operate the superconductor very close to its critical current (preferably $> 0.9\ I_c$) with safety factors reduced to a minimum.

1.3 Winding accuracy and manufacturing costs. The dipole field has to be uniform typically to 1 or 2 parts in 10^3 both for injection and extraction (and also at intermediate fields if extraction at various energies is desired). As indicated in 1.2 it is economically essential to utilise most of the magnet aperture, so that this level of uniformity should extend to at least 75-80% of the coil inner radius.

The field distribution in a high field magnet is controlled by the position of the conductors rather than by an iron profile as in conventional magnets; this gives rise to the practical problems of winding and restraining the coil to the necessary precision, and devising manufacturing techniques sufficiently simple and reliable to allow production in large numbers at reasonable cost. In addition, the choice of mechanical structure and materials must ensure that the accuracy is unaffected by thermal and mechanical cycling throughout a lifetime of, say, 10 years or more.

This level of field accuracy also presents a substantial theoretical design problem, in which the computational techniques must take account of the field distribution at the coil ends and the presence, if desired, of an iron shield situated close to the coil. In the latter case, the accurate field shape has to be maintained at all field levels despite the non-linear behaviour of the steel.

1.4 Example of cost levels. As an illustration of overall economics, it is useful to note the typical range of cost estimates for the components of a 1000 GeV superconducting synchrotron, assuming that all of the above-discussed technical objectives are successfully achieved :

(a) Superconductor ($\sim 10^5$ kilograms)	50-200 MSF
(b) Coil and cryostat manufacture	100-250 MSF
(c) Refrigeration (30-100 kW at 4.4°K)	50-150 MSF
(d) Power supply (300-1000 MJ)	50-100 MSF

These figures assume a dipole field of 45 kG, 4 cm aperture radius, and a 6-10s cycle. Closer estimates will become possible during the next few years, but it is already evident that a substantial increase in any of these items would be unacceptable.

Nevertheless, a measure of flexibility does exist - one may choose to relax one criterion slightly in order to meet another more firmly, and the apparent difference of approach evident at different laboratories frequently arises simply from the particular combination of compromises which has been chosen.

Finally we note that there exist a variety of peripheral problems such as remanent fields (arising from persistent currents within the superconducting filaments), radiation heating and radiation damage (mainly from beam loss at extraction), magnet protection during an accidental quench in one unit, transient oscillations due to coil capacitance (to earth and interturn), insulation problems, voltage breakdown in the cryogenic system, and so on. Some comments on these are included, but although not yet assessed in detail it is believed that they are compatible with existing magnet design concepts, and thus will only have a second-order effect on future designs.

2. Progress on individual problems

The preceding section represents only a brief resumé of the problems, since these have been discussed in some detail, and quantitatively assessed, in many previous papers[1,2]. We now proceed to describe the progress which has been made under the following separate headings :

Conductor and cable
Coil performance
Magnet design
Mechanical structure
Heat removal and cryogenics
Miscellaneous problems

The status of magnet prototype construction will then be summarised in section 3.

2.1 Conductor and cable

Assuming a required magnet current of $\sim$ 4000A, a required filament diameter $\sim$ 5-10 μm and current density of 1-2 x 10^5 A/cm^2 in the superconducting filaments, we need a conductor containing about 1 or 2 x 10^5 filaments. This will in general take the form of multistrand cable or braid; thus a typical range of possibilities might be as follows:

1) $\sim$ 100-200 strands, each $\sim$ 0.3-0.4 mm diameter, each $\sim$ 1000 filaments
2) $\sim$ 25 strands, each $\sim$ 0.8 mm diameter, each 4-8,000 filaments
3) $\sim$ 5 strands, each $\sim$ 1.8 mm diameter, each 20-40,000 filaments
4) $\sim$ 1 strand 4 mm diameter, $\sim$ 10^5 filaments

The choice between these depends mainly on the following considerations :

2.1.1 Composite manufacturing difficulties : composite containing $\sim$ 1000 filaments can certainly be made satisfactorily, but increasing further the number of filaments in a single wire could make it harder to prevent, for example, serious irregularities in filament diameter along the length. This (together with the need to keep manufacturing costs low) may favour options (1) or (2).

2.1.2 Self-field effects : the individual wires are twisted to prevent appreciable coupling between filaments due to the applied field, and the criteria for rate of twist are now well understood and satisfactorily verified. However, less well understood is the additional coupling which arises from the self field within the wire. This results in a non-uniform current distribution, giving extra ac losses and also the possibility of flux jump instabilities reappearing as the wire diameter increases. At what wire diameter these effects become serious is not precisely known. Our original simple self-field loss criteria (3) (indicating maximum wire diameters $\sim$ 1 mm, when corrected for a typical unidirectional waveform) are certainly safe, but probably unnecessarily stringent, since measurements at Berkeley using twisted cables have indicated that the self field loss appears to be significantly lower than the simple prediction, even with the waveform correction. There are, in fact, further theoretical mechanisms (electric centre shift in the filaments, and the twisting of the composite) which can improve current sharing, but these are not yet verified experimentally, Moreover, we have certainly seen evidence of flux jumping arising from the self field in cupronickel matrix composites as small as 0.25 mm diameter, so that with larger diameters one has to rely empirically on the copper to provide adequate dynamic stability.

The conclusion at the present time is that the physics of composites above, say, $\sim$ 1 mm diameter is not fully understood, and there is, therefore, some risk of instability in a cable option such as (3) above,(and a very high risk in cable (4).

2.1.3 Cabling : standard concentric twisted cables, although easiest to make, are also potentially subject to the self-field effects just mentioned. Furthermore, relative mechanical displacement of individual strands by an average of only a few microns can cause serious additional non-uniformity current sharing. We have, for example, observed a negative current in the central strand of a 7-strand cable (wound into a small dipole) when pulsed with a few seconds rise time (although all strands carried equal positive currents under dc conditions). It is thus generally accepted that full transposition is desirable and probably essential.

The problem is then that a transposed braid or cable has an undesirably low filling factor (perhaps 40-50%) and the large number of cross-over points between strands makes it difficult to roll or compact to a higher density (e.g. 70-80%) without breaking or damaging the strands, or excessively distorting the filaments. There has also to be a reasonable level of insulation maintained between strands in the cable. These considerations generally favour as few strands in the cable as possible, for example options (2) & (3) instead of (1), although satisfactory conductors of type (1) can in fact be made, particularly if a wide braid is acceptable.

2.1.4 Coil winding : braids and cables containing many strands are flexible and easy to wind, but are liable to result in a coil structure which is too 'spongy'. This has to be prevented by impregnation with, for example, epoxy resin, preferably filled to match the thermal contraction (metallic impregnation, e.g. solder, is also being considered, but it is then difficult to obtain a high enough interstrand resistance). With fewer strands the cable is in general more rigid, but becomes more difficult to wind, particularly as the superconducting composite is much more springy than copper.

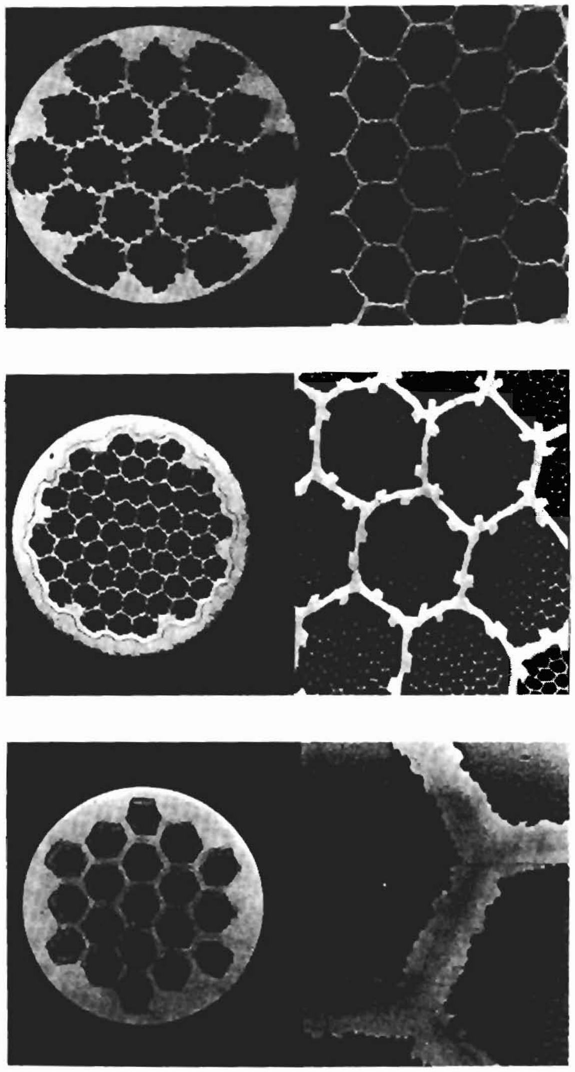


Fig. 1 Cross sections and magnified areas of some sample NbTi - CuNi - Cu composites produced

Top : 1045 filaments
Centre : 3025 filaments
Lower : 7600 filaments

These composites have a matrix/superconductor ratio ≃ 1.5

Thus we have a number of conflicting factors governing the evolution of a suitable conductor. The arguments at present favour conductors of type (1) or (2) with type (3) representing a future possible alternative.

Progress towards achieving these conductors has been very satisfactory. Some composites resulting from the Rutherford-IMI development programme and appropriate to cable types (1) and (2) are shown in fig. 1. The 1000-filament material has been available for about a year; the 3000 and 8000 filament illustrations are of first samples only but are evidently encouraging. All of these include cupronickel barriers to decrease the interfilament coupling at fast rise times (otherwise inconveniently high twist rates are needed). For rise times of, say, 10 seconds or more, the cupronickel would be unnecessary, and simpler composites with a copper matrix only would be acceptable.

The theoretical ac loss and stability properties of composites of this type have been experimentally confirmed at many laboratories, only the less important self-field effects remaining imperfectly understood.

Fig. 2 shows examples of cable types (1), (2) and (3). The type (1) 90-strand cable was made in 3 stages (6 x 5 x 3), and compacted at each stage, the final product being about 5 mm square, and 60% dense. This has however proved rather difficult to fabricate reliably without breakage, and we prefer the type 2 cable which requires only 2 stages (5 x 5) compacted to a density of about 75% metal, and is still sufficiently flexible to wind satisfactorily. The type (3) cable is relatively easy to make, but much less flexible. All these samples were, of course, made with representative superconducting composites (but fewer filaments in the case of (2) & (3) since copper cables are misleadingly simple to fabricate.

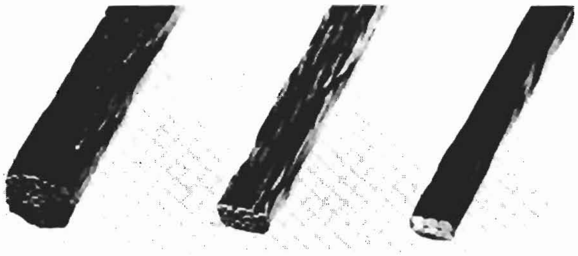


Fig. 2 Examples of compacted cables made at Rutherford Laboratory.

Left : 90 strands, 5 mm x 5 mm (∿5000A/50kG)
Centre: 30 strands, 4½mm x 3 mm (∿4000A/50kG)
Right : 6 strands, 4 mm x 2½mm (∿3000A/50kG)

It is important to note that many conductor and cabling problems would be simplified if a lower operating current (say 1000-1500A) were acceptable; however this has the various disadvantages of a lower packing factor for a given standard of insulation, a consequent less rigid coil, an increased number of layers to be wound and assembled, higher voltages during a magnet quench, and more subdivision than usual of the main power supply, We therefore assume for the present that an operating current similar to conventional synchrotron magnets is preferable. Nevertheless, it must be emphasised that lower current conductors are certainly a feasible alternative, and are, in fact, at present preferred by many designers for their greater ease of fabrication and handling.

2.2 Coil Performance

As already indicated many small coils wound from these conductors have been tested, with filament diameters down to the required 5-10μm level, and found to have pulsed losses in good agreement with theory.

The other important question is how near to their critical current they may be operated. In this connection, a key feature of the twisted multifilament composites (and in fact the original motivation for developing them) is that they do not exhibit the instability known as flux jumping which hampered earlier attempts to make satisfactory superconducting coils. Thus they are capable in principle of operating reliably very close to their critical current, and this also has been amply confirmed by a large number of tests, both dc and pulsed, on small solenoids(3) (many wound from composites containing no stabilising copper whatsoever.)

However the same investigation showed that coils may fail to reach critical current reliably if there is any source of mechanical release of energy within the coil. Thus sudden small relative conductor movements of only a few microns can provide enough frictional heating to raise the temperature locally by several degrees and thus cause a resistive transition. Such movements can be eliminated by impregnating them with, for example, oil or wax, but if a stronger material is used, such as epoxy resin, mechanical strain energy can be stored in the coil during fabrication and cooldown (due to differential thermal contraction), which may be subsquently released during energisation of the coil, by for example, cracking or relative movement near the conductor. This manifests itself by an initially low quench current, progressively 'training' to higher values during subsequent quenches, and eventually reaching a value close to critical current. In unfavourable cases this 'training' process can require many tens of quenches, and may have to be repeated after each cooldown, so that it is clearly of vital importance to understand how to eliminate or minimise these mechanical degradation effects.

Accordingly, we have carried out at the Rutherford Laboratory an extensive series of tests on about 20 similar dc quadrupole coils (fig. 3a) impregnated with different types of material. The coil parameters were chosen to be representative of typical beam transport or accelerator magnets in field (∿ 40kG), current-density (∿ 30,000A/cm^2) and internal stresses (∿ 4,000 psi, 3.10^8 dyne/cm^2) and the impregnants used were various filled and unfilled epoxy resin systems, various waxes, and various frozen liquids - ice, oil, and solid nitrogen.

The results are summarised in fig. 3b : the low yield materials (waxes, frozen liquids) showed little or no training; unfilled epoxy resin systems showed most training usually with further training after each cooldown; filled epoxy resins (with thermal contraction closer to that of the conductor) initially showed some training but little or none on subsequent cooldowns. All types eventually reached about 0.95 or more of the critical current, and this also applied to four coils assembled into a complete quadrupole magnet.

Thus we can conclude that mechanical degradation is correlated with mechanical stored energy, so that an impregnant whose thermal contraction is reasonably well matched to that of the conductor should ensure satisfactory coil performance at > 0.9 I_c, possibly after an initial 'annealing out' (during the first cooldown) of any stresses built in during fabrication.

Other ways of eliminating mechanical degradation might also be possible - for example a coil structure with no impregnation but clamped extremely rigidly to prevent relative movements even of a few microns, or an unimpregnated coil structure which allows circulation of the liquid helium (which has a high thermal capacity) around each conductor to absorb any frictional energy and thus prevent any significant local temperature changes. However, no convincing design based on these latter alternatives has yet been proposed, and it is likely that most pulsed or dc magnets constructed during the next few years will rely on impregnation techniques to achieve reliable performance plus mechanical rigidity.

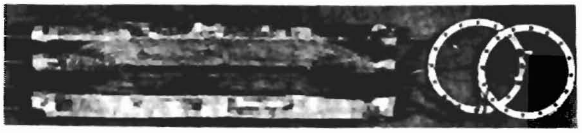


Fig. 3a One of 20 impregnated quadrupole coils used for comparative training tests

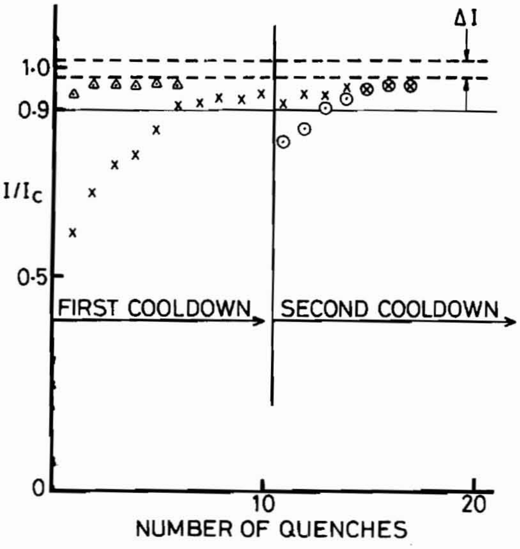


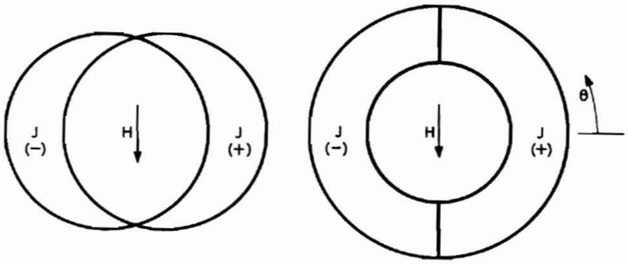
Fig. 3b Summary of typical training behaviour of impregnated quadrupole coils: Low yield materials (wax, ice, frozen oil) showed little or no training (triangles). Filled epoxy resins showed training usually on first cooldown only (crosses). Unfilled epoxy resins showed similar or more training on the first cooldown, and also required some retraining on subsequent cooldowns (circles).
The range ΔI represents the uncertainty or spread in I_c for the 1500A 18-strand transposed cable used in these coils.

2.3 Magnet design

Having discussed the production of suitable conductors, and the understanding of the conditions necessary for satisfactory coil performance, we proceed now to the magnet design and engineering problems. It is here that a variety of equally valid solutions become possible, and we begin to see differences in individual approach at the different laboratories.

Shown in fig. 4 are two idealised theoretical coil cross sections which would produce a uniform dipole field : (a) the overlapping ellipses configuration with constant current density, and (b) concentric boundaries with a cosine variation of current density.

Figs. 5(a) to 5(e) then show various ways of achieving practical approximations to one or other of these distributions, together with an indication of the appropriate conductor type, the method of heat removal, and the principal laboratories at which the various designs have been studied.



(a) $J = \text{CONSTANT}$ (b) $J = J_0 \cos\theta$

Fig. 4 Idealised coil cross sections to produce a uniform dipole field.

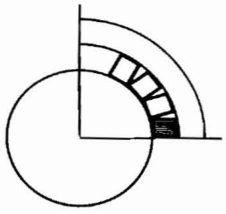


Fig. 5a Practical approximation to fig. 4(b). Each block wound from single layer of wide braid; turns spaced to give different current density in each block; conductor edge cooled by azimuthal helium channels; single layer suitable for 40-45 kG, two concentric layers for higher fields.
Studied at Brookhaven.

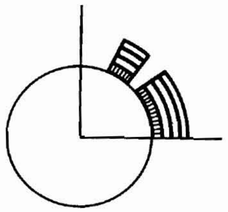


Fig. 5b Practical approximation to fig. 4(b). Spaced sectors of constant current density; wound from rectangular cable; typically 4-6 concentric layers; cooling by azimuthal helium channels or conducting mats between layers. Studied at Rutherford, Berkeley, Karlsruhe.

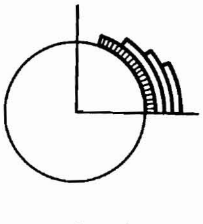


Fig. 5c Practical approximation to fig 4(a). Typically 4-6 concentric layers of constant current density; wound from rectangular cable; cooled by azimuthal helium channels or conducting mats between layers. Studied at Rutherford, Berkeley.

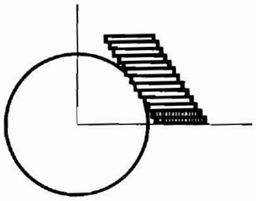


Fig. 5d Practical approximation to fig. 4(a). Shaped block of constant current density; wound in horizontal layers from narrow braid or rectangular cable; cooled by horizontal conducting mats between layers. Studied at Saclay.

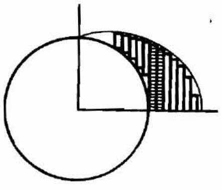


Fig. 5e Practical approximation to fig. 4(a). Shaped block of constant current density; wound in vertical layers from narrow braid or rectangular cable; cooled by vertical helium channels between layers. Studied at Karlsruhe.

Computer studies have shown that each design is in principle capable of producing an accurate field to within 70-80% of the internal coil radius provided that the prescribed coil boundaries are reproduced and maintained to within typically 0.002-0.004 cm, (random errors in conductor position are an order of magnitude less stringent). Furthermore, practical trials with copper windings have indicated that, with sufficient care, such tolerances can in fact be met using straight-forward winding techniques. In the copper dipole model shown in fig. 6, wound specifically to demonstrate this point, room temperature & 70°Kfield measurements showed that the asymmetry (quadrupole) terms were at the acceptable level of $\sim 10^{-3}$. Low temperature measurements on similar models are also planned at various laboratories. No useful field measurements on superconducting dipoles have yet been made, since the first superconducting prototypes with the necessary precision are not due to be completed until 1972-3 (see section 3).

In each case the coils will usually be surrounded by an iron shield in the general form of a laminated silicon steel cylinder. There are basically three possible locations for the steel, summarised in fig. 7. If placed some distance from the coils, for example outside the cryostat(fig. 7c), simply to reduce stray fields, it will have very little effect on the coil design but will only increase the central field by ∿ 5%. At the other extreme it may be placed immediately adjacent to the coil (fig. 7a), where it will augment the field and reduce stored energy by as much as 30-50%; in this case, however, the field in the iron in some regions exceeds 20 kG for central fields ∿ 40 kG and above, and the resulting saturation effects make it difficult to arrive at an overall design which maintains the required uniformity at all field levels. A compromise solution is to move the iron to a slightly larger radius (fig. 7b) where the gains in field and stored energy are reduced to 15-25%, but the field in the iron is now everywhere < 20 kG and there is no appreciable non-linearity.

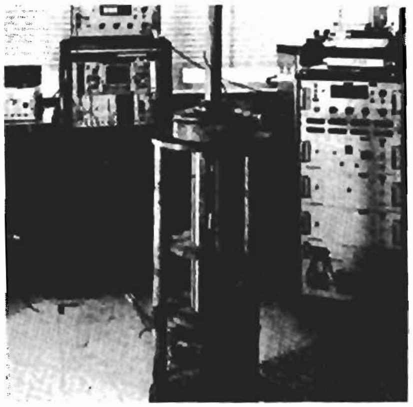


Fig. 6 High precision copper dipole model constructed at the Rutherford Laboratory, using the multilayer sector geometry of fig. 5(b). The accuracy of the field distribution was confirmed using low ac fields at room temperature and 70°K.

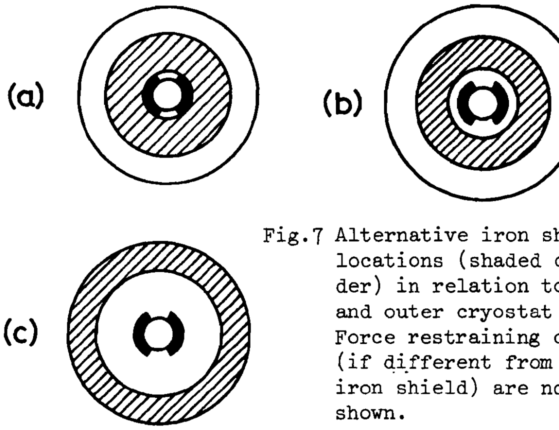


Fig.7 Alternative iron shield locations (shaded cylinder) in relation to coil and outer cryostat wall. Force restraining clamps (if different from the iron shield) are not shown.

The development of computer programmes which can accurately take into account the B-H characteristic of the steel has made it possible to study this problem in detail without the traditional necessity of building and modifying numerous trial magnets, and work is in progress at many laboratories to evaluate the possibility of adding iron to each of the coil types in fig. 5. Results so far indicate that satisfactory designs can certainly be evolved for peak fields up to 40-50 kG, even with the iron adjacent to the coil. This appears to be achievable most easily in the case of the cylindrical configurations fig. 5(a), (b), (c); a typical cylindrical shield will be 10-12 cm thick (for $\sim$ 4 cm aperture radius) perhaps with some additional shaping of the inner and/or outer boundaries. For peak fields in the 50-60 kG region and above the design becomes more difficult and the fig. 7(b) location may be preferred. Also at these higher fields, the greater volume of steel raises the magnetic hysteresis loss to a significant level.

With the less compact designs, fig. 5(d) and (e), it is probably less easy to arrive at a satisfactory design with iron close to the coil, and the gains in field and stored energy will be less. At the 40-50 kG level, therefore, it is likely that the cylindrical coil configurations will be preferred for use with iron.

2.4 Mechanical Structure

The desirability of impregnating the windings has already been discussed in connection with the prevention of relative conductor movement. For the present, epoxy resin systems will probably continue to be used for this, although, since they are brittle, it will be necessary to ensure that the local stress concentrations within and around the cable do not give rise to long term fatigue effects. Inorganic impregnants such as cements are also being investigated, since these have a low thermal contraction, and are less prone to radiation damage; they require suitable reinforcement to overcome their low fracture strength.

The resulting rigid coil structure is adequate to withstand the internal compressive forces (typically $\sim$ 4000 p.s.i., 3.10^8 dyne/cm^2) but the outward electromagnetic force acting on the straight sides of the coil (typically $\sim$ 1 ton, $\sim 10^9$ dynes, per cm length of magnet) has to be transmitted to force restraining clamps around the coil. In designs without iron at low temperature there is evidently some freedom in the method adopted to contain these forces, and various satisfactory designs have been proposed, usually involving either laminated stainless steel clamps, or a non-metallic material such as a fibre-reinforced epoxy composite.

A substantial complication of using iron immediately around the coil, is that it must then also be used to support the forces, or at least form part of the forces restraining structure; in contrast to stainless steel, however, it is a brittle material at low temperatures, and the safe working stress levels for an adequate fatigue life are at present only imperfectly understood and difficult to define with absolute confidence. One solution is to operate the iron in compression only, transmitting the forces to a stainless steel cylinder surrounding the iron; alternatively the iron can be used by itself, in tension, provided that rather conservative stress limits are adopted until more detailed low temperature fatigue data becomes available

So far we have considered only the two dimensional cross-section of the coil; another major design complication is the coil ends, where theoretical and practical requirements are more difficult to reconcile. Three-dimensional computer programmes which will accurately include the saturated iron are not yet fully developed, so that magnet designs which satisfy the required accuracy in integrated field cannot yet be specified in detail. However the physical principles of end design are well understood, and, since the required precision in end design is typically an order of magnitude less stringent than the main body of the magnet, this is unlikely to remain a significant computational problem for very long.

Practically, there are a number of ways of taking the conductor around the ends, none of them wholly satisfactory; the basic choice lies between 'bent up' ends- which are (with coil types c, d, and e) simplest to manufacture but increase the radial size of the coil, are harder to cool, and less easy to design with iron - and 'smooth ends', in which the conductors are brought round at constant radius, thus preserving the cylindrical shell structure in designs (a) (b) & (c), but increasing the axial length of the coil, and introducing mechanical difficulties such as sharper bending radii and the necessity of bending the conductor in two planes simultaneously. Evidently the end design problem could be a significant factor in choosing between different types of coil section. The theoretical design of ends, together with many other aspects of coil design has been discussed in more detail in a number of papers by Coupland 4), and Green 5).

2.5 Heat removal : cryogenics

Closely associated with the mechanical design is the choice of method of heat removal from the coil during pulsed operation.

It may be noted first of all that the use of a fully transposed cable (or braid) automatically ensures that the heat is efficiently conducted to the conductor surface (or edge) through the copper matrix of the composite. It then has only to pass through a thin layer of insulation to the liquid helium carried in a channel adjacent to the conductor. The heat dissipation involved is in the region 1 to 5 x 10^{-3} Watts/cm^3, and in order to remove this with the conductor temperature rise restricted to about 0.1°K it will usually be necessary to provide a cooling channel adjacent to every layer of the coil. This is obviously straightforward with Brookhaven design (fig. 5a) involving only one, or perhaps two, layers of wide braid. In the other cases the provision of several internal channels obviously complicates the design, and at Rutherford and Saclay the alternative technique has been studied of using laminated copper or aluminium cooling mats between layers to conduct the heat out of the coil to the liquid helium bath. It has been demonstrated that satisfactory heat transfer can be obtained in this way in a fully impregnated coil, but until it is established that the bond between the conductor and cooling mats will not deteriorate in time, the cooling channel technique will probably be regarded as a slightly safer option.

With regard to the coolant itself, we have the choice of (1) natural boiling in the static liquid, (2) forced two-phase flow at normal pressure, or (3) forced single phase flow(i.e. supercritical at several atmospheres pressure). All three are theoretically easily capable of providing the required heat transfer with channels of only 0.5 to 1 mm width, and with reasonable flow rates. Method (3) is probably ruled out by overall refrigeration considerations; of the remaining two, (1) is the simplest but is liable to involve an additional surface temperature increment of $\sim$ 0.2°K in the channel, depending on the material and nature of the surface, The choice between (1) and (2) appears, therefore, to depend partly on the result of further investigations of the latter phenomenon, and partly on the design of the overall refrigeration system.

The design of the cryostat itself now looks rather simpler than envisaged in early discussions of superconducting synchrotrons. With purely air cored magnets, field $\sim$ 60 kG, and very short rise times ($\sim$ 1 second) eddy current effects would have precluded a conventional stainless steel vessel either inside or outside the coil. However typical applications now being considered involve rather longer rise times ($\sim$ 3-4 secs) and rather lower fields ($\sim$ 45 kG) thus reducing eddy current effects by more than an order of magnitude, and allowing the use of a stainless steel cryostat with a wall thickness $\sim$ 1 mm. With iron close to the coil the situation is further simplified since, of course, the field at the outer vessel is then reduced to a negligible level. If higher fields and/or faster rise times do turn out to be necessary for any specific applications, then suitable designs have been developed either for non-metallic (fibre glass epoxy) cryostats at Karlsruhe, or for low loss corrugated stainless steel cryostats at Saclay.

Although a discussion of the overall refrigeration system is outside the scope of this paper, for completeness we note that the typical low temperature heat load arising from a pulsed magnet system might be as follows (per metre length of magnet, and per complete magnet cycle, for $\sim$ 4 cm aperture radius and $\sim$ 5-10 μm filaments):

Ac loss in filaments	50-100	J
Loss in matrix	10-20	J
Self field loss	0-10	J
Iron hysteresis loss	10-20	J
Total magnet dissipation (per cycle per metre)	75-150	J
Corresponding power for 10 sec cycle	7-15	W
Miscellaneous eddy current losses	1- 2	W
Cryostat heat losses	2- 3	W
Particle heating	0- 1	W
Refrigeration distribution losses	2- 4	W
Total loss per metre	12-25	W at 4°K

This corresponds to a total of 50-100 kW for a 1000 GeV synchrotron magnet, requiring a refirgerator input power of perhaps 20-50 MW.

2.6 Miscellaneous problems

2.6.1 Radiation effects. The concern arises principally from beam loss at ejection, which, even with the best extraction techniques, is likely to be perhaps $\sim$ 2%; for an accelerated beam of 10^{13} particles at 1000 GeV this is equivalent to an energy of 3.10^4 J. The corresponding preliminary radiation dose estimates are up to 10^{11} rad/year peak (downstream of extraction region) and perhaps 10^7 - 10^8rad/year mean, assuming all energy is released in the magnets.

Three types of problem could arise from this : firstly the radiation damage of materials, particularly of the conductor insulation and coil impregnant; secondly a serious local increase in refrigeration requirement if the distribution is as non-uniform as the above figures indicate; thirdly the danger of a local temperature rise in the worst-affected magnets sufficient to cause a resistive transition.

Work is in progress to improve the estimates of radiation dose and its distribution, and to acquire more low temperature data on possible radiation damage in both the superconducting composites and the structural materials. However, since it is only the high peak effect which is likely to be of concern, the simplest solution would appear to be to shield (by means of absorbers adjacent to the straight section) the magnets immediately downstream from the ejection septa.

2.6.2 Insulation. There has been a notorious tendency for shorted turns to develop in both conventional and superconducting coils, and it is therefore of importance to ensure a reliable standard of insulation between turns with the minimum loss of packing factor. From this viewpoint the most efficient arrangement is as few as possible turns of square section conductor, and argues against the use of lower current conductors, or large aspect ratio braids; evidently designs such as fig. 5(a), for example, would appear to run a comparatively greater risk of shorted turns. At present it is usually convenient to use a plastic or oxide coating on the individual strands in the cable, and materials such as terylene braid, glass cloth or plastic film interleaving, etc., for between-turn insulation (these may not all be suitable for long term use in a radiation environment); a wider choice of insulating materials is likely to be available in the future, including techniques for coating with suitable inorganic materials.

2.6.3 Voltage breakdown. Related to the insulation problem is the possibility of voltage breakdown to earth, via the steel shield or support, or through the cryogenic system in some way, since the magnet system will most probably be subject to a peak voltage of several kV, as with conventional synchrotron magnets. In fact, the general belief is that this will not be a serious problem with superconducting magnets, since there should be no difficulty in providing very good insulation between the coil and any metallic supporting structure, or the cryostat vessel; and breakdown through the liquid helium itself should not occur (even if in direct contact with a current junction) unless the distance to zero potential is very small ($\sim$ 0.1 mm) or unless the helium is significantly contaminated.

2.6.4 Coil Protection. Superconducting coils of high current density and high stored energy could in some cases be damaged during accidental transition to the normal state, either by internal overheating of the resistive region, or by internal voltage breakdown. This phenomenon is well understood, and the growth of the resistive region, with the accompanying internal temperature and voltage changes can be computed for any specified design to check that there is an adequate safety margin. The case of a large number of magnets in series has not yet been assessed, but it seems advisable to assume that some means of rapidly and automatically isolating any given magnet would be desirable, to prevent energy from the rest of the magnet system being released in the one resistive unit. It is, of course, unlikely that any emergency energy extraction system can be envisaged, except at the normal rate via the main power supply,since the latter is already operating at a voltage of several kV across the magnets.

2.6.5 Transients. As with a conventional synchrotron magnet, the finite capacitance to earth of the coils can result in transient current oscillations of appreciable amplitude following any sharp voltage change (e.g. at injection or flat top). It has been suggested that because of the zero superconductor resistance, these will not be damped as rapidly as in the case of a conventional magnet. No calculations for the superconducting case have yet been carried out, but it is probable that the conductor will exhibit an adequate effective ac resistance in the transient frequency range (typically $\sim$ 1 kc), and, if not, it should be relatively simple to feed in an additional ac damping voltage via a small superconducting transformer.

2.6.6 Remanent fields. For the coil geometries envisaged, the remanent field due to an iron shield surrounding the coil will be of the same order as the coercive force of the steel, i.e. $\sim$ 1 gauss. A more serious source of remanent field is the persistent dipole current circulating within each individual superconducting filament. Assuming a low field critical current density $J_c \sim 10^6$ A/cm^2, a filament diameter $\sim 5.10^{-4}$cm, and a typical space factor $\sim$ 0.2, the remanent field can be estimated to be $\sim$ several gauss. A more precise analysis including the harmonic components of the remanent field distribution, has been made by Green(6), whose calculations indicate a sextupole amplitude (using the above assumptions) of 3 to 5 gauss for a typical coil geometry with an iron shield.

The significance of this is that this is close to (and possibly already above) the acceptable limit for satisfactory injection at a field of $\sim$ 1400 gauss (i.e. 30 GeV injection energy for 1000 GeV at 45 kG) and if the low field J_c happens to be higher (perhaps up to 5.10^6 A/cm^2) then the remanent field error would limit the possible injection energy to a higher level. However, if necessary it is likely that a modification in the processing of the superconductor (e.g. the heat treatment) can be found which will restrict the low field J_c on acceptable value.

3. Magnet Prototype Development

From the preceding discussions it is apparent that sufficient is now known about each aspect of pulsed magnet design to allow us to proceed to the design and construction of pulsed magnet prototypes which meet the required synchrotron magnet specification in almost all respects. In fact, it is a specific objective of the three European laboratories engaged in this work to have one or more of such prototypes operational, and to have completed preliminary like tests, by the end of 1973. These projects will represent the culmination of a planned series of progressively more realistic pulsed models constructed during the preceding years.

As an example, the table below summarises the stages in pulsed magnet development at the Rutherford Laboratory during the period 1967-73.

Following the development of filamentary composites during 1967-8, we distinguish five phases in the model magnet programme, labelled AC1 to AC5. In the first phase, which involved the testing of solenoids only, the stability and loss predictions for various individual composites were successfully verified under pulsed conditions.

The second stage included the construction of a small pulsed 35 kG dipole of simple 'racetrack' shape, wound from a 1500A cable, and impregnated in paraffin wax. This also operated close to the expected critical current, with losses as predicted; no deterioration of performance occurred after several thousand pulses with rise times between 1 and 10 seconds.

Time scale for pulsed synchrotron magnet development		
1967 1968		Development of filamentary composites
1969	AC1	Performance tests on solenoids
1970	AC2	35kG 'racetrack' dipole, 25 cm long, 4 cm aperture, 1500A cable
1971	AC3	Sector geometry dipole 40 cm long, 40 kG at 10 cm bore, or 45 kG at 8 cm bore, 5000A cable, 1-2 sec. rise time, cooling mats, epoxy resin impregnation
1972	AC4	Horizontal 45 kG accurate dipole, cylindrical geometry, iron shield, 5000A cable, 3 second rise, 40 cm long, 9 cm bore, cooling channels, filled epoxy impregnation
1973	AC5	Demonstration horizontal prototype refined version of AC4, 100-200 cm long

This year, we have completed the construction of AC3, a 40 cm long, 10 cm bore dipole wound from a 90 strand 5000A cable (see fig. 2) using the fig. 5(b) coil shape (with six concentric layers); heat removal is by laminated copper cooling mats between each layer, and the impregnant is unfilled epoxy resin. This magnet is shown in figs. 8 and 9, and in its initial tests has been pulsed continuously at over 90% of critical current, reaching ≈ 40 kG with a 2 second rise time. An additional inner section to this magnet is being constructed to increase the field to ≈ 45 kG in an 8 cm bore. The measured ac loss was ≈ 10w at a 2 second rise time, consistent with the predicted value for 8 μm filaments.

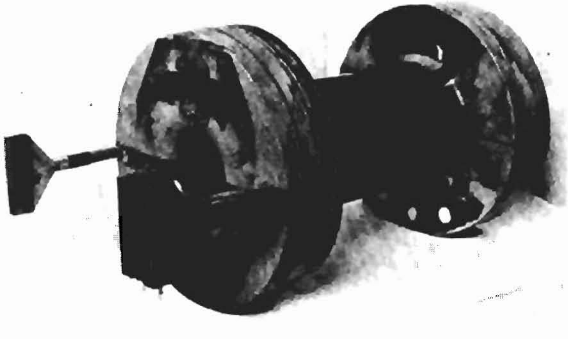


Fig. 8 Impregnated coil system of Rutherford Laboratory pulsed dipole model AC3

The next magnet, AC4, is now in the design stage and is expected to be tested by mid-1972. This will be a horizontal, accurately wound dipole using coil type 5(c) or 5(b); an improved cable (25 strands of 2000 filament composite) giving a higher overall current density will allow a field of 45 kG to be reached with only four concentric layers surrounded by a cylindrical iron shield. The impregnant will be a filled epoxy resin, and heat removal will be by natural boiling in azimuthal cooling channels between each layer. AC4 is intended to be as close as possible to a fully satisfactory design, so that the design of the 1973 prototype, AC5, is proceeding in parallel and is expected to differ in detail only. Thus the purpose of AC4 is (a) to safeguard the programme by providing advance confirmation of the validity of the AC5 design, and (b) to provide a test bed for trying out design variations in, for example, the coil or iron shield. Possible cross-sectional dimensions for AC4 and AC5 are shown in fig. 10. The cable for AC5 has not yet been specified, and will depend on the state of development of the various composites such as those illustrated in fig. 1.

Fig. 9 Complete AC3 test assembly, showing coil clamps and 10,000A current leads.

With parallel programmes at other laboratories based on the various other coil types in fig. 5, it is clear that by the end of 1973 we can expect to have had sufficient operational experience to be able to assess the feasibility, cost, and optimum designs appropriate both to pulsed superconducting magnets suitable for synchrotrons and to their dc counterparts for storage rings.

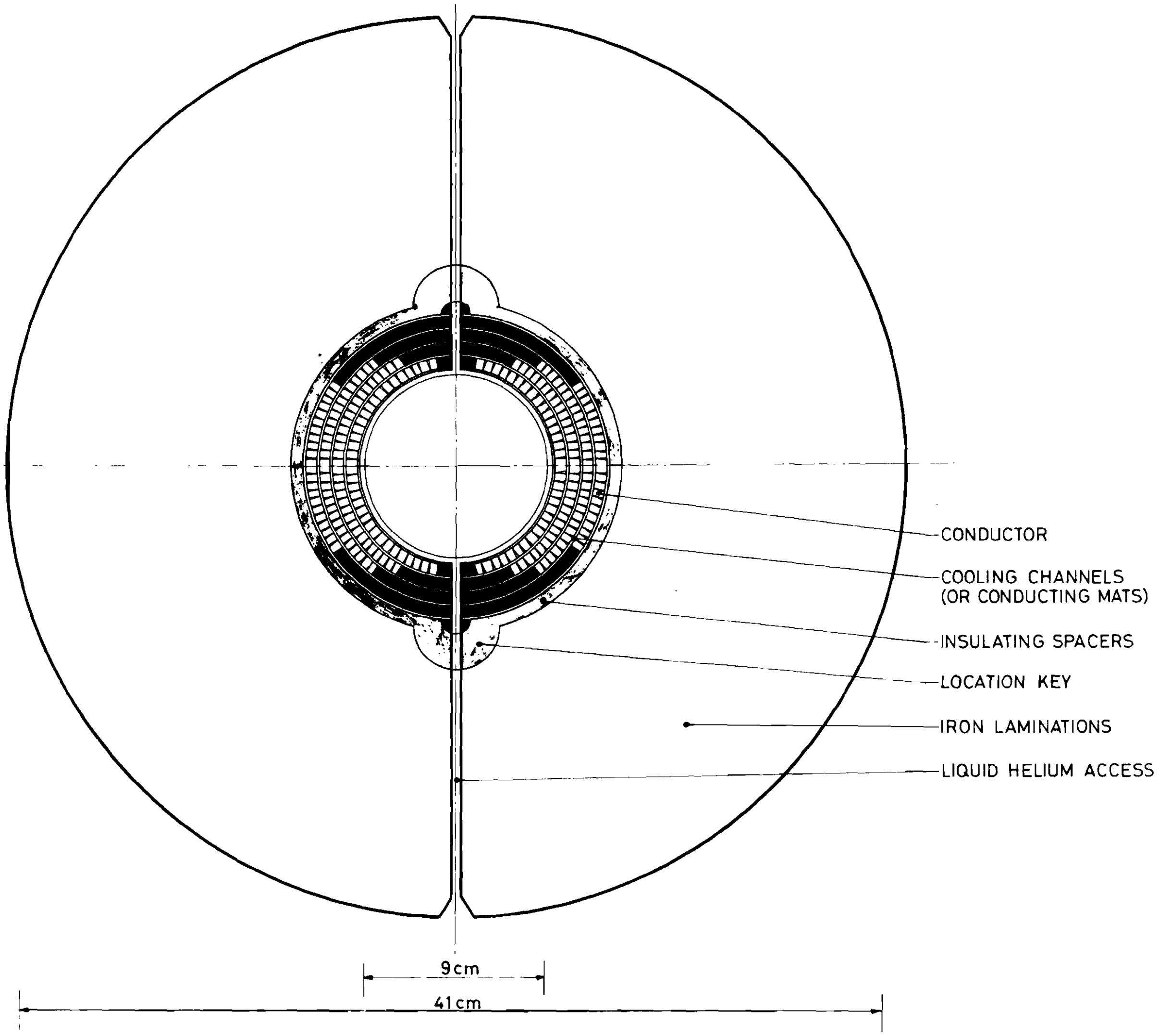


Fig 10 Approximate dimensions and features of a possible cross-section for models AC4 and AC5.

Acknowledgements

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DISCUSSION

E.G. KOMAR: I would like your opinion about the optimisation of the magnetic field value. If you used 30 kilogauss instead of 40 - 60 kilogauss, the cost of the wire would be smaller, there would be fewer mechanical problems, the power-supply cost would be less, and only the tunnel cost would be greater.

P.F. SMITH: It is true that if one is considering a completely new accelerator, on a new site, and has the freedom of optimising the total cost, then the optimum magnetic field does turn out to be rather lower - typically in the region 35 - 40 kilogauss.

However, at the present time most of this work is directed towards the possible conversion of existing accelerators, which involves keeping within an existing site area, and probably an existing tunnel. In this situation, one aims for a higher field to allow the highest possible particle energy.

E.D. COURANT: How do the difficulties in various aspects of magnet design change if one thinks in terms of rise times of minutes rather than seconds?

P.F. SMITH: At very slow rise times, or in d.c. magnet systems, heat transfer and power supply problems are eased, refrigeration loads are less, and the superconducting composite specification is less stringent. However, one still has the same problems of achieving an accurate magnetic field, a reliable high current density performance, and a rigid mechanical structure. Thus essentially the same technology is required, but the task is significantly easier and one might more readily contemplate magnetic fields as high as 60 - 65 kilogauss.

G. BRIANTI: What about superconducting materials working at higher critical temperatures, such as Vanadium-Gallium (V_3Ga) or ternary alloys in filamentary form?

P.F. SMITH: Materials such as niobium-tin and vanadium-gallium are brittle compounds, which are very difficult to manufacture in a mechanically satisfactory filamentary composite. In principle, they are potentially very attractive in allowing operation at rather higher fields and temperature but, although some progress has been reported in making samples of such materials (in the following paper by Dr. Green, for example) it is not yet clear whether one could manufacture this reliably in large quantities at reasonable cost, nor how many years it might take to be able to do this.

L. TENG: How about this new material NbAl which is supposed to be better mechanically?

P.F. SMITH: This material is of essentially the same type as those just mentioned. I believe it is probably just as brittle, and presents similar fabrication problems.

J.B. ADAMS: Is it yet possible to say whether industry could manufacture thousands of super-conducting magnets with the reproducibility required by a synchrotron?

P.F. SMITH: During the past few years we have been concerned mainly with establishing the principles and conditions necessary for achieving reliability and accuracy in a single magnet. There is little doubt that these conditions could be duplicated in a large number of magnets, and one of our main preoccupations during the next two years will be to evolve an engineering design which is sufficiently simple to ensure this reproducibility at a reasonable manufacturing cost.

R. WIDERØE: Can you tell us more about radiation damage, possibly closely related to lifetime? What will happen if the beam hits the wall?

P.F. SMITH: Under normal operating conditions, the most serious problem is the beam loss at extraction, which would probably be concentrated in the magnets immediately downstream. Even a 1 - 2% beam loss would probably cause enough local heating to quench the magnet in this region, and some form of shielding along the straight section has to be envisaged.
The mean radiation dose around the ring is estimated at 10^7 - 10^8 rads/year and does not present a serious problem.

An occasional accidental loss of the whole beam may well cause local temperature rises of many degrees and quench many of the magnet units. In this situation an electrical protection system will ensure no damage due to overheating of the resistive regions.

G. SALVINI: Which is the area of the 8 - 10 cm bore which can be usefully filled by the beam?

How do we compare (precision and useful area) the bore of an S.C. magnet with the useful gap within the donut of a conventional synchrotron?

P.F. SMITH: Our objective is to design the coils so that the useful field region extends to about 75 - 80% of the bore, so for an 8 cm diameter bore the useful area will be a circle of about 6 cm diameter.

B.W. MONTAGUE: Is it possible to convert the circular useful field region into a more familiar elliptical shape by choice of winding configurations and tolerances?

P.F. SMITH: Windings can be designed to produce an aperture of any aspect ratio. However, for a large horizontal to vertical aperture ratio, the quantity of superconductors and the stored energy are usually much greater, and it is preferable to evolve an overall machine and lattice design which utilises a nearly circular aperture.