RECENT WORK ON SUPERCONDUCTING SYNCHROTRONS

J. D. Lewin, P. F. Smith, and A. H. Spurway
Rutherford High Energy Laboratory, Chilton, Berkshire, England

Introduction

Our previous general studies of superconducting synchrotrons \(^1,2\) have suggested that these could be significantly cheaper than conventional synchrotrons, as well as offering other attractive possibilities such as the conversion of existing machines to higher energies, and the reduction in size of multi-TeV machines, where site selection might otherwise become problematic.

Inevitably, at this relatively early stage, many assumptions are made in these studies; but, in our opinion, only three are crucial to the feasibility of superconducting synchrotrons:

(a) that a conductor with a sufficiently low ac loss can be developed which is also stable at high current densities;

(b) that the magnets can be constructed, aligned, and kept aligned, with accuracies similar to those achievable with conventional synchrotron magnets;

(c) that suitable non-metallic materials can be found for the mechanical support, electrical and thermal insulation, and cryogenic enclosure of the magnet system; these materials will have to be able to withstand continual pulsed stresses and insulation, and occasional thermal cycling, for many years without deterioration.

There is, of course, the additional proviso that solutions to these three problems must be cheap enough to leave the overall economics undistorted; in particular, we would hope that large quantity production of the conductor could result in prices below those of existing materials.

We first concentrated our efforts on conductor development, since realistic detailed consideration of the other problems is impossible without some knowledge of the conductor's properties, the thermal environment it requires, etc. So, in collaboration with Imperial Metal Industries Ltd. (U.K.), we have been developing filamentary conductors suitable for both dc and ac applications; the development programme and its present state are described below.

Following completion of the small scale tests we plan to begin constructing and testing preliminary coil-pulsed magnets. Also, we are now turning our attention to the problems described in (c) and (c) above, hoping eventually to unite the results of studies of these problems with the model magnet tests to produce some fully realistic prototype synchrotron magnets.

Finally, we have been investigating realistic magnet lattices, both to establish typical parameters, and to see if any special problems or benefits arise from the use of high field magnets.

Conductor Development

Our general studies indicate that, for superconducting magnets to be competitive in synchrotron applications, the conductor must satisfy two criteria:

(a) Peak overall current densities in excess of \(3 \times 10^4 \text{ A/cm}^2\) must be reliably achieved.

(b) The ac loss must be reduced to about 20-30 W per metre of machine circumference.

Both these requirements can be met by the use of composites containing fine superconducting filaments; filament diameters need to be below typically 50 pm to satisfy (a)\(^3\), and about 10 pm for (b). It was clear, therefore, that both problems - as well as the stabilization problem for dc magnets - could be attacked in a single development programme. This programme is outlined in reference 3; more detailed papers are in preparation. Here we simply summarize the results so far obtained, and discuss their apparent implications for the design of pulsed magnets:

Stability

Small scale tests show that the stability of twisted filamentary composites improves with decreasing filament diameter, as predicted, and should be adequate for the majority of coil applications for filament diameters about 50 pm or less.

Tests have been made on d.c. coils producing up to 60 kG in 9 cm bore, and containing up to 3 kg of twisted filamentary composite (61 filaments, niobium titanium/copper ratio up to 1:1, overall diameter 0.03 to 0.05 cm. Manufactured by I.M.I. under the trade name "Niomax FM"). These initially showed some residual degradation; but this was apparently due to wire movement, since after vacuum impregnation with paraffin wax they reliably reached their full short sample current.

Highest overall current densities achieved so far are (for a coil space factor of about 0.55):

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\begin{array}{ll}
58,000 \text{ A/cm}^2 \text{ at } 50 \text{ kG} \\
46,000 \text{ A/cm}^2 \text{ at } 40 \text{ kG} \\
40,000 \text{ A/cm}^2 \text{ at } 30 \text{ kG} \\
32,500 \text{ A/cm}^2 \text{ at } 60 \text{ kG} \\
\end{array}
\]

The results obtained so far therefore support
our belief that stable and reliable performance can be obtained with a solid, externally cooled, coil structure. However, we do not yet have any real understanding of the circumstances under which degradation can result from wire movement. Despite the success of the simple wax impregnation technique (even with the more sensitive cupro-nickel composites), our initial tests on small coils fully impregnated with epoxy resin have not given such reliable results, and a great deal of work remains to be done before one can be confident of eliminating this source of degradation - particularly under long-term pulsed conditions.

Ac losses and ac transport currents

Calorimetric measurements of losses in coils of twisted composites containing filaments in the region 20 μm to 50 μm are in agreement with theory. There is therefore nothing new to report regarding the losses themselves; and a filament size of 10 μm or less still looks to be the most desirable (and feasible) objective.

However, we have now made some measurements of transport current in coils under ac conditions, to check that the decrease in critical current can be entirely accounted for by the temperature rise resulting from the ac losses. Small (about 5 kg) coils of various niobium-titanium/cupro-nickel composites were used, and the maximum transport current was determined, using a continuous triangular waveform, for frequencies up to about 10 kHz.

The qualitative behaviour was as expected - the critical current decreases as frequency increases, and the reduction increases with filament diameter. But the observed reductions in current - e.g. 25% at 0.5 kHz for 20 μm filaments - were greater than expected from the coil geometry and thermal conductivity. However, a more detailed theoretical treatment showed that the discrepancy arose from the fact that our simpler treatment failed to take full account of both the field and temperature dependence of critical current. This correction has the important consequence that the allowable temperature rise in the magnet windings is much smaller than we had previously believed - perhaps only 0.05 K for a current reduction of 5% at 60 kG peak field. This makes it even more desirable to achieve a high average thermal conductivity in the windings (>1000 W/cm K) and may also necessitate cooling on both sides of the winding.

On the basis of these results we can make a first attempt at specifying a suitable conductor for synchrotron applications. As explained in reference 3, the conductor must be twisted at a pitch determined by the resistivity of the matrix and the field rise-rate. Assuming a requirement of 60 kG/cm, the twist pitch would be impractically small with a copper matrix, and a higher resistivity material such as cupro-nickel is needed. With such a matrix, however, coil protection would be extremely difficult; and, whilst this need not matter in an actual synchrotron (operating within established safety margins), it would clearly be an embarrassment during magnet development and testing. It is therefore desirable to include a proportion of copper in the composite, which would also assist in satisfying the requirement for a high thermal conductivity.

Consequently, for our initial model magnet studies, we propose to use three-component composites (e.g. various configurations of niobium-titanium, cupro-nickel, and copper).

Model Work

Once we have satisfactory results from small scale tests on three-component composites, we plan to begin a model-test programme. To form a realistic magnet conductor, the basic wire (typically 0.05 cm diameter carrying about 30A at 60 kG) will be made up into a transposed cable carrying several thousand amperes. First models will probably use epoxy resin impregnated windings, though we are looking for alternative materials with higher thermal conductivity.

Studies of the problems in achieving the necessary structural accuracy and stability have begun; and we would hope to incorporate the results of these and of materials studies in future model magnet designs, so arriving at realistic prototypes for eventual synchrotron magnets.

Lattice Studies

We have made some preliminary studies of specific synchrotron designs, round the possibility of converting and extending the 7 GeV weak focusing synchrotron Nimrod. Details are presented in reference 4, as well as indicating the substantial possible advantages in such conversion schemes, these show that, for a given beam intensity, significant aperture reductions can result from the use of higher fields - provided that positional errors and proportional field errors are no greater than with conventional magnets.

References

1. P. F. Smith and J. D. Lewin, Nuclear Instrum. and Methods 52, 298-308 (1967)
2. P. F. Smith, Proceedings of Brookhaven Summer Study on Superconducting Devices and Accelerators (to be published) (1962)
4. J. D. Lewin and P. F. Smith, Rutherford Laboratory Memo. HHEL/M.161