PULSED SUPERCONDUCTING MAGNETS*

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INTRODUCTION

The possibility of achieving substantial economic gains by using superconducting magnets in large proton synchrotrons has inspired an experimental program at Brookhaven aimed at investigating the properties of pulsed superconducting magnets. Some of the measurements resulting from this program have been described during this Summer Study[1] and elsewhere.[2,3]

There are two main aspects to the use of such magnets in accelerators: the first being that the losses incurred during pulsed operation must be low enough to make their use economically desirable, and the second that the magnets must operate in a reliable and predictable manner. I shall concentrate on the latter aspect, that is, how the devices we have been testing perform as magnets and how much they must be improved before they will become serious candidates for use in future high energy machines.

EXPERIMENTAL DETAILS

With the exception of one coil all the magnets tested were made using ½ in. wide Nb_3Sn conductor clad with a small amount of copper or silver. This material was chosen because of its very high current density potential. High current density is required in synchrotron magnets in order to minimize the energy stored in the windings and thus the size and cost of the power supply.

The coils are of identical geometry with an i.d. of 2.5 in., an o.d. of 6 in., and a length of 0.5 in. (i.e., single spiral windings of ½ in. wide conductor). Figure 1 shows a typical ribbon magnet and plastic former. The slots in the end plates allow liquid helium access to approximately 60% of the ribbon edges. Electrical insulation is provided by ½ in. wide Mylar ribbons of various thicknesses. A commercial inductance bridge was used to measure the coils during winding to ensure that there were no shorted turns.

A programmable 100 kW motor generator was used to pulse the magnets with a triangular current waveform similar to that used in synchrotrons. The losses were determined by measuring the boil-off gas produced during pulsing. This method is described elsewhere in the Proceedings.[1]

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1. G.H. Morgan and P.F. Dahl, these Proceedings, p. 559.
2. W.B. Sampson et al., in Proc. 6th Intern. Conf. High Energy Accelerators, Cambridge, Mass., 1967, p. 393.
3. G.H. Morgan et al., J. Appl. Phys., in press.

EXPERIMENTAL RESULTS

The results are summarized in Table I. The numbers appearing in quotation marks after GE refer to the nominal critical current of these ribbons at 100 kG. Coils 2, 3 and 4 are made of the same material but with fewer turns, the reduction in winding density being achieved by using thicker Mylar insulation. Those currents marked with an asterisk represent the critical currents for the values of the field listed in the table and indicate that these magnets are not limited by instabilities. The figures in brackets in the maximum power column are the cycle times used in seconds which represent approximately twice the rise times. The current densities are for the total magnet cross section and include the insulation. The maximum energy flux was calculated from the peak power assuming that 60% of both edges of the ribbon was exposed to helium and includes a factor which takes into account the nonuniform production of energy in the coil.[1]

The dependence of the loss on magnetic field is shown in Figs. 2 and 3 where the "Q", or energy loss per cycle divided into the stored energy, is plotted against field.

TABLE I

	Magnet	No. of Turns	Maximum Current (A)	Current Density (kA/cm^2)	Maximum Field (kG)	Maximum Power (W)	Energy Flux (W/cm^2)
1	GE "150"	371	515*	35	41	6.6(2)	0.09
2	GE "300"	350	680*	42	50	10.5(2)	0.12
3	GE "300"	175	960*	30	36	9.8(1)	0.22
4	GE "300"	122	1280*	28	33	12.0(1)	0.38
5	RCA	168	600	20	22	5.5(1)	0.16
6	GE "600"	175	800	25	30	5.0(1)	0.14
7	CSF	553	276	30	33	11.0(2)	0.30
8	T48B	1195	50	11	13	2.7(2)	-

DISCUSSION

As the results show, simple magnets can be pulsed to high current densities and, in fact, in some cases to critical currents in times of the order of one second. The poorest performing magnet was constructed from NbTi wire of 0.019 in. diam which was copper clad and insulated to a total diameter of 0.025 in. This poor performance is probably due in part to the fact that this coil did not have helium in contact with all the turns, but the low "Q" indicates that this material has considerably higher losses than Nb_3Sn, at least in wire form.

All the Nb_3Sn coils behave in essentially the same way but with a number of interesting differences. The "Q" of the CSF coil does not go to very high values at low fields despite the fact that this material is similar to the GE ribbon. Another notable difference is in the performance of the two magnets made from materials capable of very high "short sample" critical currents. These coils, 5 and 6, of RCA and GE "600" ribbon respectively, do not reach critical current and in fact quench at energy dissipation rates considerably lower than some of the other magnets. This suggests that the early quenches are not due to difficulties in transferring the heat produced during the field change from the edges of the normal material to the helium bath but rather in getting the thermal energy from the superconductor into the normal metal cladding. The reason for this effect may be due to the poor conductivity of Nb_3Sn which would lead to larger temperature gradients across the thicker high current samples. A similar effect would result, of course, from a poor bond between the superconductor and the normal metal.

CONCLUSIONS

The results are summarized in the following statements (see also Ref. 1):

1) The loss per cycle is independent of frequency (at least in the range investigated, 0.1 to 60 Hz). This means that "Q" is independent of frequency in marked contrast to conventional magnets whose "Q's" decrease with frequency approaching zero for dc operation.

2) The loss is approximately proportional to the square of the average of the component of field perpendicular to the surface of the ribbon. This means that, for a considerable range of field, the "Q" is independent of field.

3) Fields as high as 50 kG and current densities up to 42 kA/cm^2 have been achieved in simple magnets using pulses with rise times of the order of one second.

4) The current density in a pulsed superconducting magnet cannot be increased by simply increasing the thickness of superconductor since there appears to be a limit set by the thermal conductivity of the superconductor itself. A reduction in loss would presumably lead to improved current density.

The results indicate that the goal[4] of 60 kG pulsable dipoles operating at 60 kA/cm^2 with "Q's" in excess of 1000 may be obtained in the near future, particularly in view of the promise of the subdivided conductors now under investigation.[5]

4. W.B. Sampson, these Proceedings, p. 998.

5. P.F. Smith, these Proceedings, p. 913.

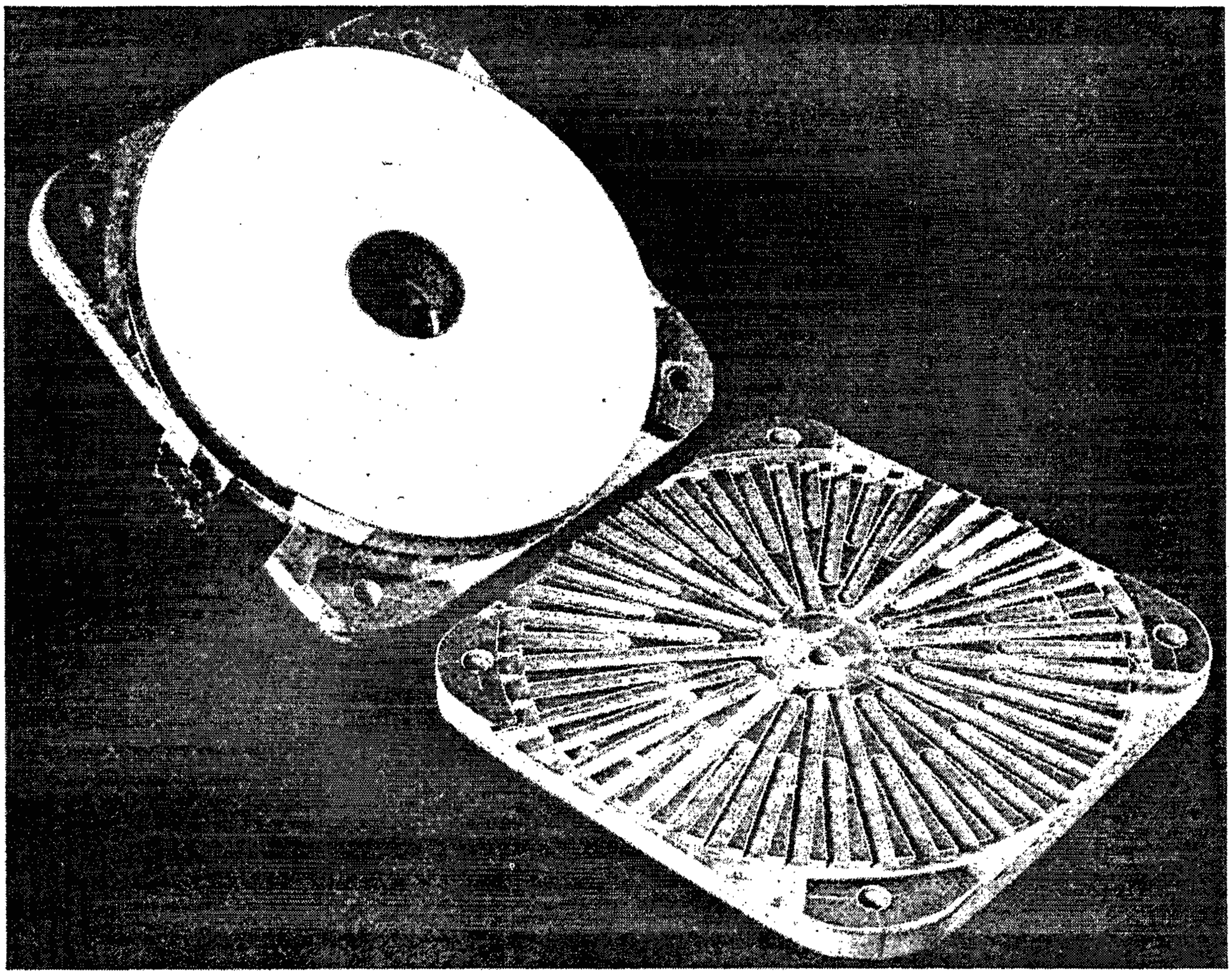

Fig. 1. Pulsed magnet and plastic former.

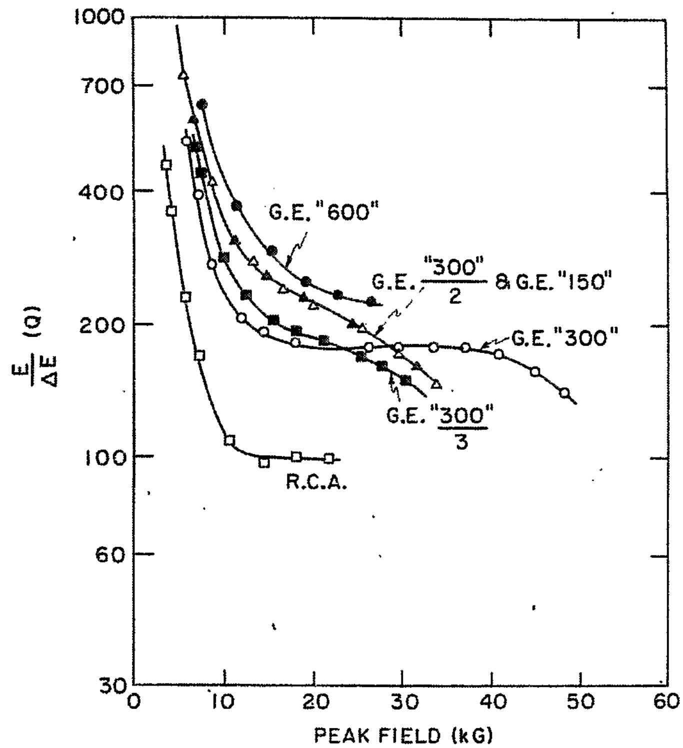

Fig. 2. "Q" plotted against field for pulsed magnets.

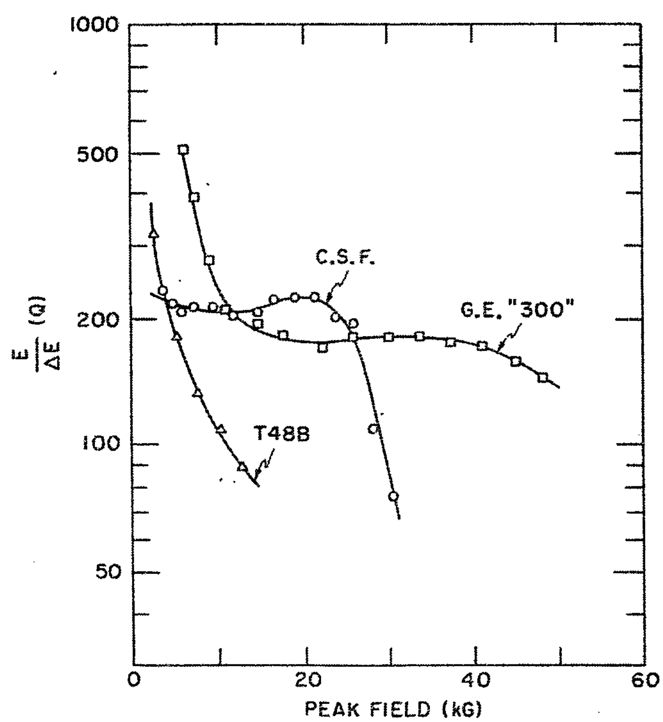

Fig. 3. "Q" plotted against field for pulsed magnets.

INTRINSICALLY STABLE CONDUCTORS

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It is generally believed that flux jumps are the only real obstacle to obtaining reliable short sample performance in superconducting coils. The sudden local release of energy results in a premature transition to the resistive state and prevents the reliable attainment of high current densities. Even in large, fully-stabilized coils, the flux jumps which could occur in wide conductors might in some cases release sufficient energy to cause an undesirably large temperature rise, perhaps of the order of 15-25°. This is discussed in a separate paper.

During the last few years, the development of realistic theoretical models for the electrical and thermal processes which occur during a flux jump has led to some remarkably simple criteria which indicate that flux jumping should be absent in superconducting wires typically less than about 0.002 in. in diameter, and in certain arrangements of superconducting filaments and normal metal.

There is, therefore, an obvious incentive to try to develop conductors using these criteria. With this objective, theoretical and experimental work has been in progress at the Rutherford Laboratory since early 1967, and was reported briefly last year.[1] Closely related to this is the possibility of developing a conductor with an ac loss small enough for use in pulsed synchrotron magnets, which could also be achieved by the use of finer filaments.

Since the beginning of 1968 the scale of this work has increased, and experiments are being carried out on samples and small coils of a wide variety of filamentary composites developed in collaboration with Imperial Metal Industries, Ltd. (U.K.). Although the initial tests are encouraging in many respects, much still remains to be done and we would not normally publish any results at this stage. However, in view of the growing interest in this possibility, we have agreed to set down the essential features and principal conclusions of the theory, and to summarize the experimental results obtained so far, as a guide to those planning similar programs, but with the reservation that some of our statements may turn out to require modification in the light of further experimental data.

We discuss the subject under the following headings:

- Theory of single filaments of superconductor.
- Theory of composites of superconductor and normal metal.
- Conductor configurations being tested.
- Description of the four types of test being used.
- Main results so far.

More detailed accounts of both theoretical and experimental work will be published at a later date.

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1. P.F. Smith, in Proc. 2nd Magnet Technology Conference, Oxford, 1967, p. 543.