TEST RESULTS – PULSED SUPERCONDUCTING SYNCHROTRON-TYPE DIPOLE MAGNETS*†

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Summary

Seven 10-cm bore superconducting pulsed dipole magnets for synchrotron application have been built. The first three were random-wound; in the others, the conductor is arranged in an ordered array with radial helium coolant passages. Central fields of 2.7 T have been attained with no iron return yoke. In pulsed operation to 2.4 T at a rate of 0.4 T/s the losses were about as predicted. The newest magnet is wound with a simple cable, rolled to a square cross-section, and containing forty-nine .02-cm-diam wires. An improved insulation-ventilation system enables the space factor to be twice that of the preceding magnet.

1. Introduction

In the winter of 1969-1970, progress in the production of fine, twisted, multifilament, NbTi superconductor and success in building pulse solenoids led us to the decision to build pulsed dipole magnets for superconducting synchrotrons. A reference magnet design that could serve to test various superconductors and winding methods was developed. (Fig. 1) The inside bore of the winding is 10 cm; a cold bore is employed; the winding is 3 cm thick, sufficient for a central field of 5 T at the short-sample limit of various superconductors containing 7 to 10-μ-diameter filaments. The support structure and helium vessel are nonmetallic, and the room-temperature iron return yoke is not saturated. At a 5 T central field the magnetic stored energy is 300 kJ per meter, and the cyclic losses are about 200 J per meter per cycle.

Six pulse dipoles with these general dimensions have been tested from June 1970 to May 1971; a seventh has been completed.

2. Random-Wound Magnet Construction

Virtually all commercial electromagnetic devices using small round wire are produced by the fast and inexpensive random-winding method--no attempt is made to place the turns in an orderly array. Our interest in the application of the method to small superconducting beam-transport magnets goes back many years. When Peter Smith underscored the virtues of twisted multicore conductors at the 1968 Summer Study at Brookhaven our interest was renewed, and we set about developing the method.

Early attempts at LBL at winding a dipole--Summer of 1968--were unsuccessful; as the wire accumulated in the end region, the inward pressure developed by the outer turns caused the ends of the inner turns to collapse and loosen. Pacific Electric Motor Co. (PEM), engaged to continue the effort, developed two successful winding techniques. In the first method, a series of flat, oval-shaped coils of increasing size were wound from a continuous piece of wire on a stepped collapsible form, then removed, and forced into a dipole-shaped mold. In the faster second method, the coil was wound directly into its proper dipole configuration as in the earlier attempts at LBL, but after about 1/8 of the turns had been wound, steel pins were inserted into the winding form at the ends, and the next 1/8 of the turns were wound around those pins; additional pins were inserted, and so forth.

To ensure that the windings would maintain their shape when removed from the winding form: (a) the coil, in its mold, was immersed in a diluted epoxy resin, then removed, and the excess resin allowed to drain away before curing, or (b) the wire had a coating of a thermoplastic material which softened and bonded to adjacent wires when heated. Dummy magnets, when sectioned, exhibited a sufficiently uniform distribution of the turns.

Glen Lambertson invented an end shape for layer-wound multipole magnets which produces no end effect in the integral sense.[2] Ends for the random-wound dipole were designed which approximated the Lambertson design. This design involves winding around dowel pins as in the PEM method, and is only negligibly more complicated. Early in 1970 a set of dipole windings was produced by PEM with unskilled labor in three man-days. (Fig. 2)

In addition to enabling magnets to be produced in a large volume at low cost, the random winding method results in a high space factor (Tables I and II). However, there are disadvantages:

For fine superconducting filaments (5μ), the single multicore wire probably cannot be made to carry more than a few hundred amperes, resulting in a large-inductance, high-voltage magnet. Many magnets would have to be connected in parallel to match power supplies of reasonable design.

During construction and operation the thin insulating coating on the wire has often broken down. Thicker coatings would reduce the space factor and the thermal conductance.

As no well defined coolant passages are provided, heat must be removed by conduction if the magnet is potted, or by percolation if it is not. Perhaps a high conductivity potting material would be beneficial.

2.1 Magnet #1

This magnet was wound from single-strand wire having a thermoplastic coating, Butvar B-73 (Monsanto Chemical Co.), over the basic Formvar (Shawinigan Resins Corp.) insulation. After winding, the magnet was heated, causing the Butvar to soften and fuse.

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† A more complete version of this paper is presented in Ref. 1.

This provided sufficient bonding of the wires to permit handling of the two magnet coils, but individual wires could be easily teased from the coil. After the magnet had been operated, the conductors were found to have been compressed toward the midplane by the Lorentz forces; the maximum wire motion was about 1 cm. The magnet was then impregnated with paraffin wax to immobilize the conductors, and the maximum field increased from 2.3 T to 2.85 T in the ends, some 65% of the material short sample performance measured along the load line.

2.2 Magnet #2

A 7-wire simple cable conductor (Table II) was used in this test. Only one pole was used, and the magnet was vacuum impregnated with paraffin wax and wrapped with filament-wound fiberglass epoxy. The transition current was 80% of short sample on slow charge, and the measured pulse loss was small, as expected. No shorts or wire movement were apparent. When pulsed, the poor heat transfer restricted the average power generation to about 1 W. In cycling between zero and 1.5 T the $\dot{B}$ was limited to 0.1 T/s.

After the removal of some of the wax, small wire movement could be detected, upon charging, through loud clicking noises and jumps in the $\dot{B}$ coil signal. On slow charge the maximum current was reduced 25%. In cycling between zero and 1.5 T some three times as much heat could be removed, so the $\dot{B}_{max}$ was increased to 0.3 T/s.

2.3 Magnet #3

The conductor was a cable having 49 Formvar-insulated wires of 0.022-cm-diam. with 10 μ filaments. The entire cable was double wrapped with polyester tape, further reducing the helium cooling. Despite this extra insulation the finished winding had numerous shorts, and the performance was poor.

3. Orderly Wound - Uniform Current Density

While the random-winding technique appeared to be well suited to the small single-strand wires, an orderly winding technique seems more appropriate to the high-current multi-strand cables. Three orderly-wound magnets were made. (Fig. 3) Each layer was wound radially from inside to outside, and a crossover from the outside of one layer to the inside of the next was made at one end. In the first two magnets, the crossover was insulated by cambric sleeving which was slotted to allow helium permeation. The maximum field in the ends was 40% higher than the central field. On the third magnet, the average current density in the ends was decreased by inserting spacers between the layers, and the crossovers were laid into grooves in the spacers. These magnets were slow to wind since the conductor, turn-to-turn insulation, and radial coolant passages had to be assembled simultaneously.

These magnets were wound with a 49-wire cable conductor resulting in a low space factor (Tables I and II). The low space factor results in low current density and a non-rigid structure. Good cooling compensated for some of these deficiencies.

3.1 Magnet #4 (Fig. 4)

The Formvar-coated wires of the simple cable had an open spiral wrap of silicone fiberglass 0.1 mm thick. Radial cooling passages were provided by strips of polyester 0.4 mm thick inserted between layers. A thin iron return yoke was wound around the outside of the magnet using 1.25-mm-diam iron wire, used to minimize eddy currents. No shorts developed during thousands of pulses and dozens of transitions. The low cyclic losses were what one would calculate for the hysteresis losses in the 7 μ filaments alone.

Conductor movement, heard as clicking noises, prevented short sample performance. However, the transition current was not dependent on the charge rate up to the 0.5 T/s limit of the power supply, which we attribute to the excellent cooling provided by the radial passages. We attribute the degraded performance to poor stability caused by the organic insulation on the wires coupled with mechanical motion in the spongy coil structure. The transition current was increased 50% through a program of pulsing and charging to transition at various voltages.

When the iron return yoke was removed, exactly the same current limit was achieved, although the field was only 2/3 of the previous value. The magnet was then vacuum impregnated with paraffin wax. The transition current was reduced 10%; naturally, the heat removal rate was severely reduced.

3.2 Magnet #5

Magnet #5 was identical to #4 except that the individual composite wires were coated with a silver-tin solder, Stay-Brite 8, instead of an organic insulation. A spiral wrap of silicone-fiberglass was used on the cable, and a flat nylon braid was placed between turns. The coil was slightly more spongy than in Magnet #4, and conductor movement could be detected when the magnet was charged.

The magnet achieved short-sample performance (96% on the first transition) at all charge rates. The excellent cooling seemed to counteract the conductor movement, and the conductor movement did not add to the low cyclic losses, which were in agreement with those expected for 7 μ filaments. There were some small, intermittent shorts, but the magnet still reached its short-sample behavior.

When the iron-wire return yoke was tightly wound around the magnet, the shorts became worse and the performance was badly degraded. When the magnet was disassembled, burned conductor was found.

3.3 Magnet #6

The form for Magnet #5 was modified to expand the ends (Fig. 5) to reduce the field rise in the ends from 40% above the central field to about 10%. Thicker insulation between turns was used, but the same system of layer-to-layer insulation with radial spaces was continued. The conductor from Magnet #5, with the obviously burned-out sections removed, was reused. It is possible that some of the conductor used was damaged, and also that the shorts were developed between layers in the gaps between the radial cooling slats.

The magnet, when run with an iron-wire return yoke, acted as though it had internal shorts or high resistance regions, was degraded, and was very charge-rate sensitive. Badly burned conductor was found upon disassembly.

4. Orderly Wound - Two Current Densities

Magnet #7 has two conductor blocks (in each quadrant); they have the same width but different current densities; the lower current density is achieved by inserting thicker spacers between the layers. This lower current density results in only a moderate field rise in the end loops--about 10% higher than the central field. (Fig. 6)

There are no layer-to-layer crossovers, as the magnet is made by winding outward on one layer, inward on the next, and so forth. This is possible because each layer is shaped as if it were formed from a flat straight strip bent by simple curvature into its final shape. For such a shape, there is no tendency for any part of any turn to fall inward or outward due to the wire tension. Turn-to-turn insulation is provided by flattened fiberglass sleeving impregnated with a B-stage epoxy resin. As the resin is tacky in its partially cured state, it sticks to the conductor when forced against it by rollers as the conductor is wound onto the magnet. Layer-to-layer insulation is provided by a continuous strip of polyester film to which intermittent spacers have been applied to provide radial helium passages.

The large increase in space factor through the use of compacted cable and thinner insulation can be seen in Tables I and II. Helium cooling channels are provided on both sides of the square cable.

5. Future Plans

The compaction of simple cables or transposed braids seems necessary to achieve high coil current densities. Structural rigidity also depends on a high space factor, although various organic or metallic impregnants can be used, provided the thermal and electrical properties of the coil are not thereby degraded. The testing of the compacted cable requires extensive experimentation which we plan to carry out on several conductor and insulator systems through solenoid and dipole magnet tests. Dipole performance and its relationship to details of construction will continue to be studied through the building and testing of a number of magnets of full-size cross-section without the complication of the horizontal nonmetallic cryostat.

References

[1] W. S. Gilbert, R. B. Meuser, and F. Voelker, Test Results -- Pulsed Superconducting Synchrotron-Type Dipole Magnets, Lawrence Berkeley Laboratory Report LBL- 335 Sept. 1971.

[2] R. B. Meuser, End Effects in Superconducting Beam-Transport Magnets, IEEE Trans. on Nuc. Sci., NS-18, [3], 677 (June 1971).

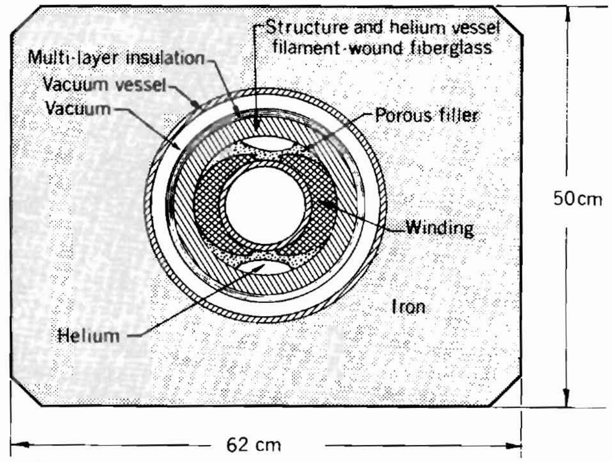

Fig. 1. Reference design for a superconducting synchrotron magnet.

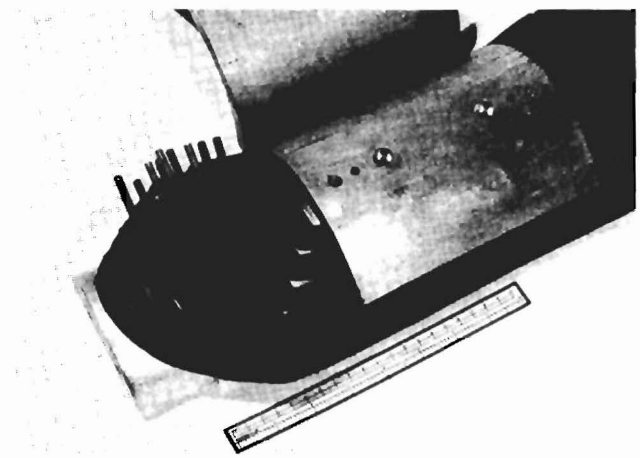

Fig. 2. Random-wound magnet having Lambertson ends.

Table I. Space factor; fraction of coil cross-section occupied by composite metal conductor.

Single wires:	
Hexagonal array, single wire, no insulation	.91
Square array, single wire, no insulation	.79
Achieved, Magnet No. 1, Formvar insulated, average over entire coil cross-section	.58
Simple cables laid in square array:	
1 layer over central wire; 7 wires	.61
2 layers over central wire; 19 wires	.60
3 layers over central wire; 37 wires	.59
Compound cables laid in square array:	
7 ropes of 7 wires each = 49 wires	.48
7 ropes of 19 wires each, or 19 ropes of 7 wires each } = 133 wires	.46
Compound cables compacted to square:	
Maximum achieved; 49 wires	.76
Maximum achieved; 133 wires (1 broken wire)	.85
Full-transposed braid, compacted:	
Square cross-section, 48 wires	.67
Rectangular cross-section, 2:1, 48 wires	.61

TABLE II - Magnet Descriptions

Magnet number	Wire and cable	SC filament diam	Description	Winding inside diam and thkns	Space factor	Turns per pole
1	1 mm diam 2.0 Cu/SC, 355 filaments Butvar/Formvar ins. Single wire*	30μ	Random wound	102 mm 25.4 mm	0.58	1062
2	0.5 mm diam 2.0 Cu/SC, 355 filaments Formvar insulation 7-wire cable	15μ	Random wound Single pole tested	102 mm 25.4 mm	0.45	476
3	0.23 mm diam 1.3 Cu/SC, 200 filaments Formvar ins. 40-wire cable*	10μ	Random wound. Cable insulated with half-lapped polyester tape. Single pole tested.	102 mm 25.4 mm	0.34	250
4	0.2 mm diam 1.1 Cu/SC, 400 filaments Formvar ins.	7μ	Orderly wound. 2 current blocks with same current density. Radial cooling passages.	102 mm 25.4 mm	0.25	204
5	0.2 mm diam 1.1 Cu/SC, 400 filaments Stay-Brite insulated*** 49-wire cable**	7μ	Orderly wound. 2 current blocks. String insulation between turns. Radial cooling passages.	102 mm 27.4 mm	0.28	221
6	Conductor same as in magnet #5 above. Possible damage when magnet #5 shorted.		Same as Mag. #5 except ends expanded.	102 mm 27.4 mm	0.21	170
7	0.2 mm (8 mil) diam 1.25 Cu/SC, 211 filaments Stay-Brite insulated***	10μ	Orderly wound, 2 current blocks with different current densities. Epoxy fiberglass between turns bonded to conductor. Radial cooling passages.	76 mm 32 mm	0.58	340

* Cryomagnetics Corporation, 4955 Bannock St., Denver, Colorado 80216
** Norton Company - Supercon Division, 8 Erie Drive, Natick, Mass. 01760
*** J. W. Harris Co., 10930 Deerfield Rd., Cincinnati, Ohio 45242

TABLE III - Magnets' Performance

Magnet number	Test description	B_{max} (T) Central field	End field	% Short sample	$\dot{B}_{max}$ $\frac{T}{sec}$	Q or u_{max} / (Δu)/cycle	Coil current density kA/cm^2
1	Whole dipole - unimpregnated	1.9	2.3	41	~ .05	Shorts	12.1
	Whole dipole - wax impregnated	2.4	2.8	50	~ .05	Shorts	14.8
	Half dipole - without and with wax	1.3	2.5	45	.15	160	16.6
2	Half dipole - no wax	1.3	2.4	70	.2	220	15.3
3	Half dipole - no wax	0.8	1.5	50	~ .01	~ 75 (shorts)	10.4
4	Whole dipole - iron return	2.3	3.2	70	> .5	500	11.6
	Whole dipole - no iron	1.5	2.1	45	> .5	480	11.6
	Whole dipole - wax impreg., no Fe	1.3	1.8	40	.29	420	10.4
5	Whole dipole - no iron, no wax	2.7	3.8	100	> .4	600	19.5
6	Whole dipole - iron return	2.6	2.9	80	~ .2	Shorts	13.0
7	Whole dipole - no iron	4.0*	4.5*	100*	--	---	28*

*Estimated values. Magnet #7 has not been operated.

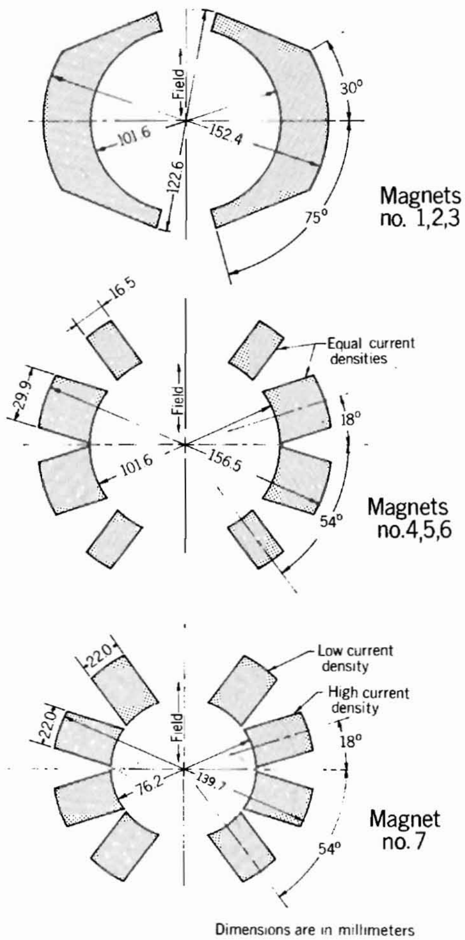

Fig. 3. Winding cross-sections.

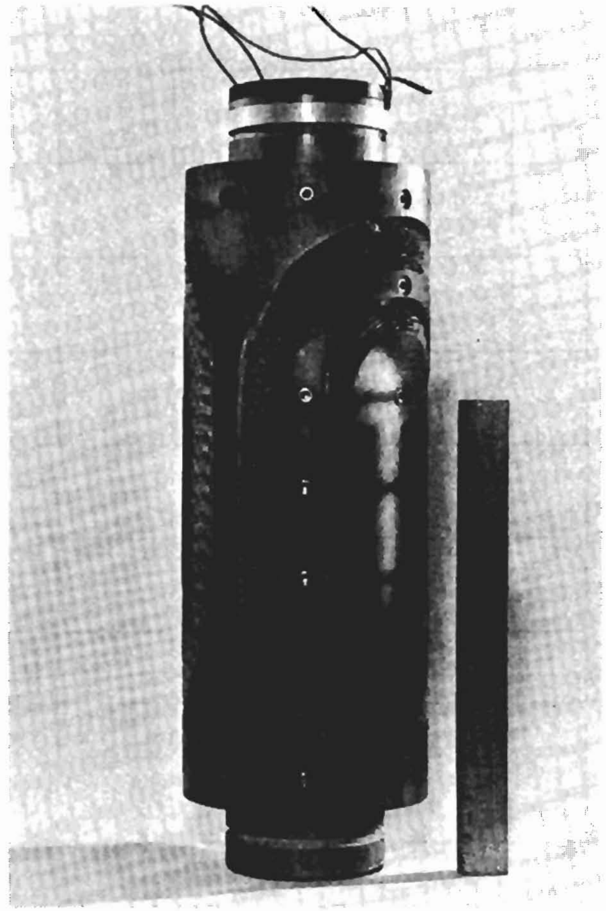

Fig. 4. Magnets #4 and #5.

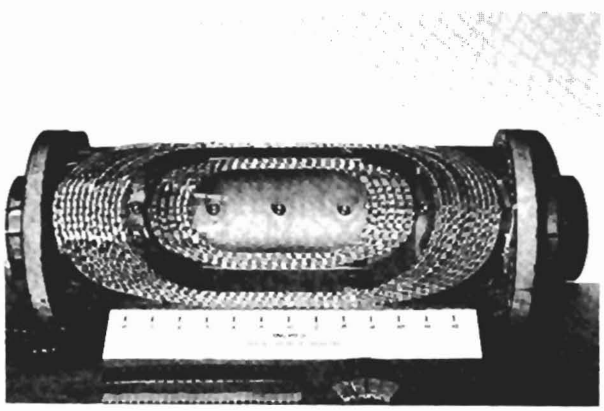

Fig. 5. Magnet #6, having expanded ends.

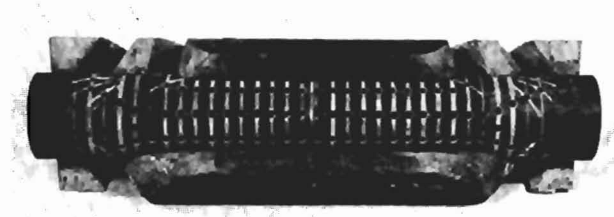

Fig. 6. Winding form for Magnet #7.

DISCUSSION

P.F. SMITH: I would like to comment on the use of a 49-strand cable with only partial transposition of the strands. Measurements have indicated that many of the strands in such a cable may carry zero or even negative currents under pulsed conditions, and may also be liable to self-field instability. Therefore, we feel that a fully transposed cable will be essential for a synchrotron magnet. Are you planning any dipoles wound from fully transposed cables?

W.A. WENZEL: In our new tests, especially with magnet No. 7, our immediate interest is in improving the space factor through compaction. It seems that with simple cables a higher compaction factor can be obtained, than with fully transposed cables. What you say is relevant, however, and we may soon try fully transposed cable, depending on the test results from magnet No. 7.