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Summary

AC, or cyclic, energy losses were determined in geometrically similar solenoids wound with single-core, untwisted-multicore, and twisted-multicore composite superconductor. The losses were larger in the untwisted-multicore conductor than in the corresponding single-core case. When the multicore conductor was twisted, the losses were markedly reduced. The multicore conductor, when both twisted and untwisted, was remarkably free of flux jumps; thus the filament diameter of 0.0013 in. may be small enough to provide intrinsic stability.

Introduction

The feasibility of pulsed superconducting magnets in accelerators depends critically upon the heat generated, which must be removed by 4.2°K liquid helium. The attendant temperature rise tends to drive the superconductor resistive, or normal. The energy loss for a cyclic sweep of magnetic field is akin to hysteresis, and for single-wire filaments, loss per unit volume is proportional to wire diameter. Practical accelerator magnets appear to require 0.001-in.-diam (25μ) or smaller wire. Coextrusion of many filaments of ductile NbTi imbedded in copper or copper alloy enables one to produce the required fine filaments within a strong, high-current conductor. However, the normal material causes increased losses through electrical coupling of the filaments. This coupling can be reduced with high-resistivity normal material and by twisting the entire matrix.

These cyclic losses have been measured in single-core NbTi superconductor-wound solenoids and the results and comparison with theory reported by us.[1] The coextruded multicore conductor resulting in filament sizes between 0.001 and 0.002 in. did not become generally available until late 1968. P. F. Smith and his co-workers pointed out that the potential advantage of small filament size would not be realized if the normal matrix material were able to electromagnetically couple the filaments.[2] Dependence of matrix coherence length ℓ_c on the properties of the composite conductor and the rate of magnetic field change $\dot{H}$ is

$$\ell_c^2 \approx 10^8 \lambda\, J_c\, d\rho/\dot{H}, \qquad (1)$$

where λ is the space factor, J_c is the current density (A/cm^2), d is the diameter of the superconducting filament (cm), and ρ is the electrical resistivity of normal material (ohm-cm). If the wire is twisted so that half the twist distance is smaller than ℓ_c, the filaments are not coupled, and the cycle loss per superconductor unit volume should correspond to the filament diameter, d. If the half-twist distance is greater than ℓ_c, the filaments are coupled, and the cycle loss increases to that corresponding to the much larger dimension of the entire matrix.

A solenoid wound with Supercon .015/.030 in. conductor was tested for cyclic, or pulsed, energy loss.[1,3] Developmental material was supplied by Airco. This multicore material has the same quantity of superconductor and the same OD, but the core is subdivided into 131 0.0013-in.-diam. filaments. This material was wound into a solenoid of the same dimensions as that of the single-core case, and the magnet was tested for cyclic energy loss.[4] This Airco material has now been twisted 1.5 turns per in. and rewound into the same solenoid configuration. The pulsed loss data for this last magnet are included in this report, together with relevant data from the previous two tests.

Experimental Arrangement

Figure 1 is a photograph of the test magnet. An important feature of the construction is that the conductor surface is chemically oxided, and this oxide serves as the turn-to-turn insulation. Fiberglass cloth is used for interlayer insulation. As will be seen, this method of coil insulation is not satisfactory. Details of the experimental apparatus and procedure are presented elsewhere.[1,3]

Experimental Results

The solenoid(s) specifications are:

Winding: ID = 1.5 in., OD = 4.5 in., length = 4.5 in.; Inductance = 1.3 henry;
Maximum field on axis = 70 kG at I = 120 A;
Stainless steel flanges and winding spool.

All three test magnets performed at their respective short sample limits; the multicore Airco conductor has slightly lower J_c than the single-core Supercon conductor. The heat transfer characteristics are such that the magnet goes normal at about 10 W average power, although slightly higher power can be dissipated during single-pulse operation.

*Work done under the auspices of the U.S. Atomic Energy Commission.

Figure 2 displays the cycle loss vs I_{max} for all three magnets. It is apparent that there is a dramatic reduction in the loss for the twisted multicore as compared with the single core, but that the untwisted multicore has approximately twice the loss of the single core. All these data were either taken at very low frequency, 0.02 Hz, or extrapolated to zero frequency.

The dependence of coherence length and loss on frequency or $\dot{H}$ is predicted by Eq. (1). For the twisted multicore solenoid, the loss per cycle vs frequency is presented in Figs. 3 and 4. The superconducting loss per cycle should be constant, and the linearly rising part, apparent in Fig. 3, is of the form expected for both eddy-current loss in the normal material or resistive loss due to faults in the insulation. The magnitude is many times too large for eddy currents, and so we presently attribute the effect to shorts in the insulation. At very high $\dot{H}$ we would expect to see a rapid rise in loss, due to the coherence length getting shorter than the half-twist length. In Fig. 4 these rapid rises are observed at many sweep currents and at values not far from those predicted by Eq. (1). However, when the triangular waveform was changed to one with 31-s thermal-recovery periods between the triangular pulses, the region of rapid rise was moved to far higher $\dot{H}$, in contradiction to Eq. (1).

Discussion

Clearly subdivision of the superconductor can reduce ac loss when the filaments are kept divided through twisting or some other technique. The quantitative determination of the coherence length in terms of the superconductor and magnet properties and dimensions from our measurements seem to be in disagreement with Smith's prediction, but the differences are in the user's favor; the twist required seems to be much less than predicted. Since much of our measured loss is due to insulation faults, we are applying Formvar insulation to the twisted multicore conductor and will retest the solenoid when rewound. The results of those tests together with solenoid and dipole magnets wound with multicore conductor utilizing Cu and high-resistivity CuNi alloy will be published elsewhere.[5]

References

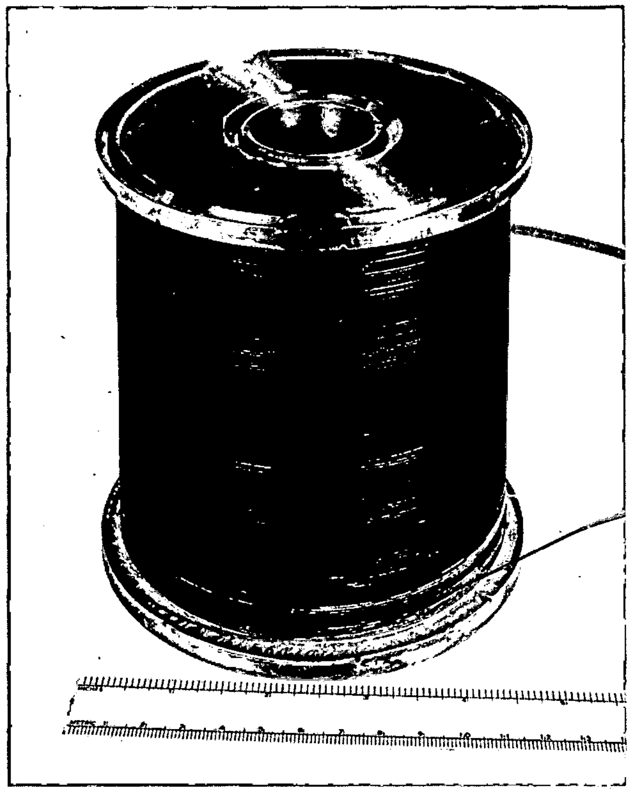
1. W. S. Gilbert, R. E. Hintz, and F. Voelker, Lawrence Radiation Laboratory report, UCRL-18176, April 1968.

2. P. F. Smith, et al., 1968 Summer Study on Superconducting Devices and Accelerators, Brookhaven National Laboratory, UAC-15655, to be published.

3. F. Voelker, Lawrence Radiation Laboratory report, UCRL-18374, July 1968 and 1968 Brookhaven Summer Study, UAC-15655, to be published.

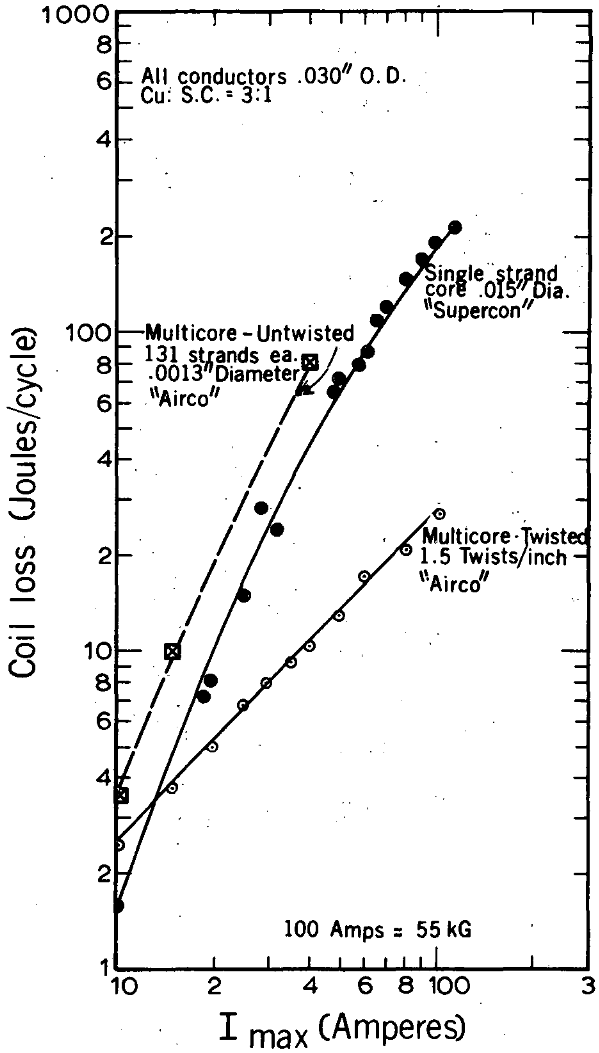
4. W. S. Gilbert, 1968 Brookhaven Summer Study, UAC-15655, to be published.

5. W. S. Gilbert and F. Voelker, Lawrence Radiation Laboratory report, UCRL-18780, to be published.

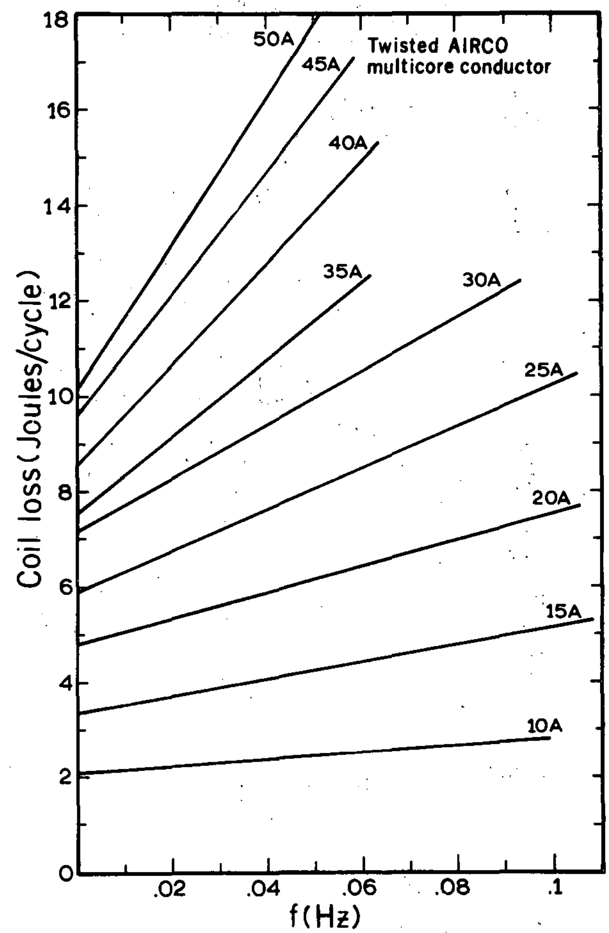


CBB 682-749

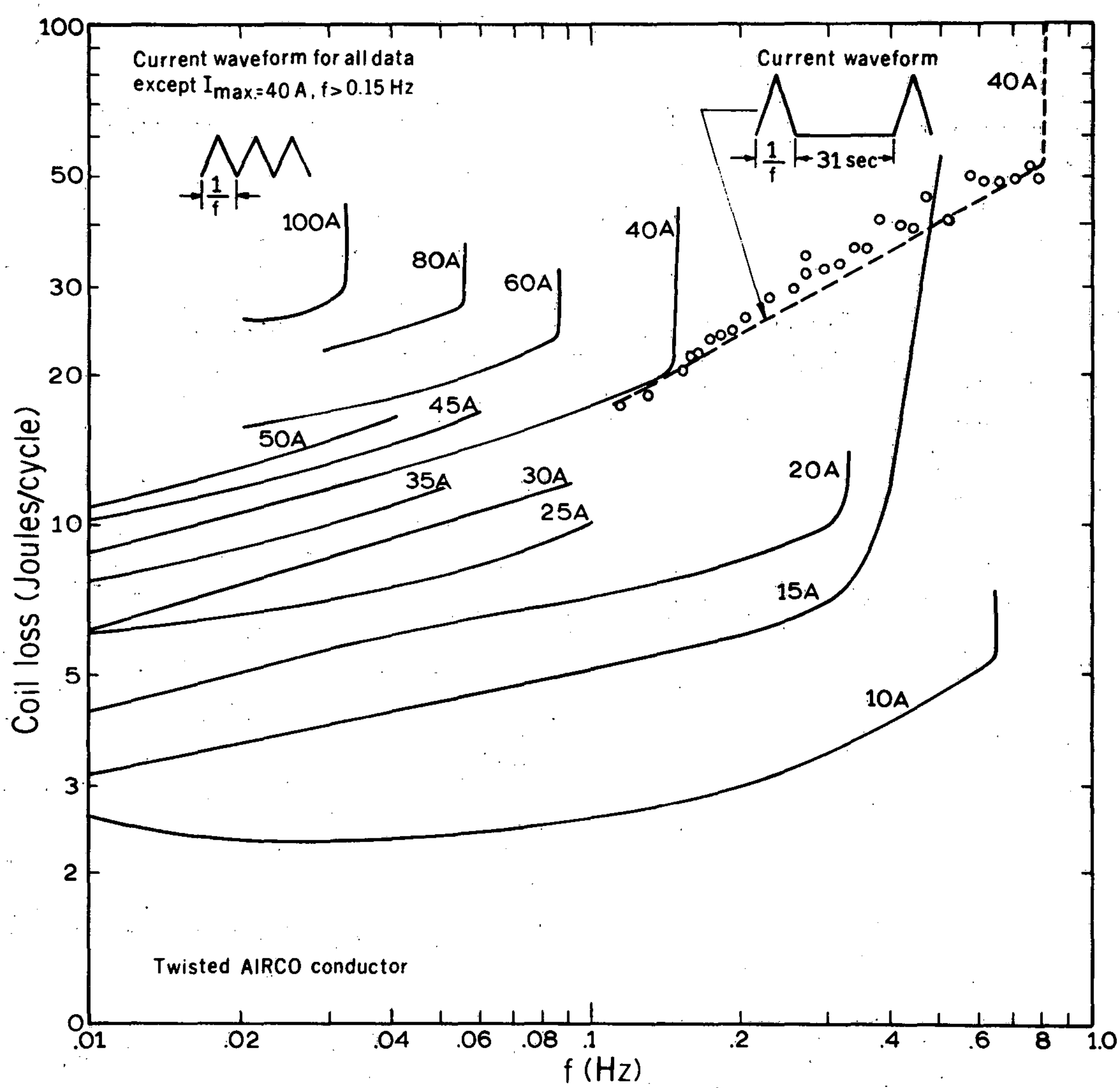
1. Test Solenoid(s)



2. Solenoid cyclic energy loss V_s maximum sweep current for three test solenoids.



3. Solenoid cyclic energy loss V_s frequency for twisted multicore conductor.



4. Solenoid cyclic energy loss V_s frequency for twisted multicore conductor. For I_M = 40A and f > 0.15HZ, the f refers to the triangular portion of the current waveform.