Presented at the 1986 Applied Superconductivity Conference Baltimore, Maryland September 28–October 3, 1986

QUENCH PROPAGATION ACROSS THE COPPER WEDGES IN SSC DIPOLES

BNL--38853

DE87 003472

A. K. Ghosh, K. E. Robins and W. B. Sampson
Brookhaven National Laboratory
Upton, New York 11973

Abstract

The effect of copper wedges on quench propagation in SSC windings, has been studied. The The results indicate that the turn-to-turn quench transit time for conductors separated by an insulated copper wedge can be predicted with reasonable accuracy from the bulk quench properties and the mean wedge thickness.

Introduction

The rate of development of resistance in a quenching superconducting magnet determines if the coil can absorb its stored energy without damage. If resistance builds up rapidly enough the magnet can be protected by a passive system utilizing cold diodes. A more complicated system of active quench protection is required if natural resistance development is insufficient to prevent conductor overheating at the origin of the quench.

Estimating the resistance build-up of a specific magnet design requires knowledge of the quench propagation velocity along the turns (longitudinal) and from turn-to-turn (transverse). When wedges are included in the windings for field shaping they alter the transverse propagation and further complicates estimating the quenching behavior of the magnet.

The transverse and longitudinal quench velocities have been measured for SSC dipole windings including cases with very thick insulated copper wedges.

Experimental Details

Simulated windings formed from molded SSC conductors [1] were equipped with small heaters and voltage taps and mounted in the bore of a 6T dipole. This is illustrated in Fig. 1 which shows the clamping fixture used to provide compressive prestress. The effect of conductor keystone and wedge angle were taken into account by alternating the thick sides to form a rectangular assembly. Velocities were determined by timing the passage of the normal front between voltage taps with a multi-channel digital oscilloscope. The uniform field region of 70 cm is long enough to give accurate longitudinal velocities and the low field regions prevent the normal front from traveling around the ends before crossing transversely. In measuring the wedge transit times two identical wedges were used with four conductors as shown in Fig. 1 and the results averaged for the four values obtained by triggering a quench in either conductor and measuring the transit time across both wedges. To determine the bulk properties eight conductors were used in a series arrangement.

* Work Supported by the U. S. Department of Energy.
Manuscript received by September 30, 1986.

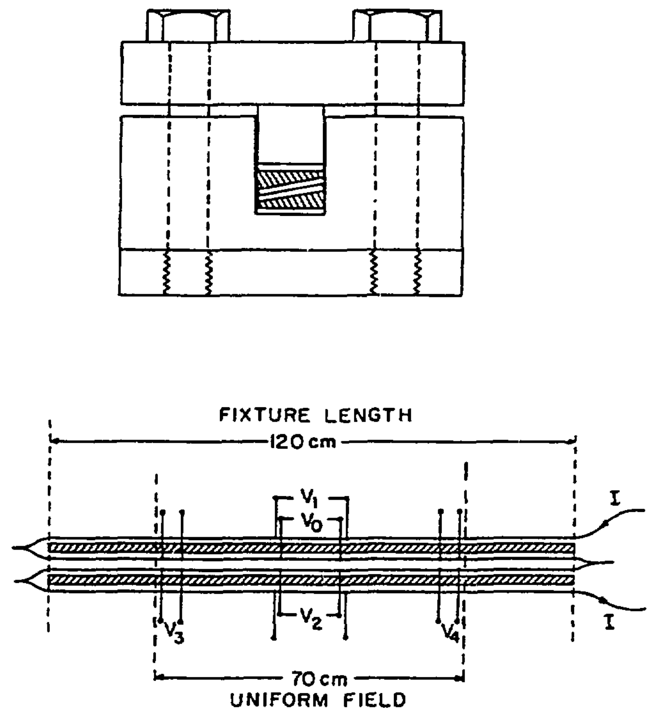

Figure 1. Experimental arrangements for measuring longitudinal and transverse quench velocity in simulated SSC dipole windings.

Longitudinal Velocity

The velocity of propagation of the normal front along a superconducting cable is strongly influenced by the maximum current that the conductor will carry without spontaneously reverting to the normal state. For insulated conductors inside a winding, this "quench" current is approximately equal to the critical (10^{-12} ohm-cm) current.

The longitudinal velocity measured at 5T for a number of cables with different maximum currents, I_m, is shown in Fig. 2 as a function of transport current. Velocity-current relationships of this type can be represented conveniently by the expression given in Fig. 3 [2,3] where A is the cross-sectioned area, T_0 is the excess temperature (i.e. $(T_c(H)-T_{bath})$ and $\kappa\rho$ is the product of the normal state resistivity and the thermal conductivity. The function $f(i,\xi)$ contains the cooling conditions and is almost independent of ξ for reduced currents ($i = I/I_m$) above 60% of the maximum current. Also shown in Fig. 3 is a fit of this expression to the 9.2 kA cable of Fig. 2.

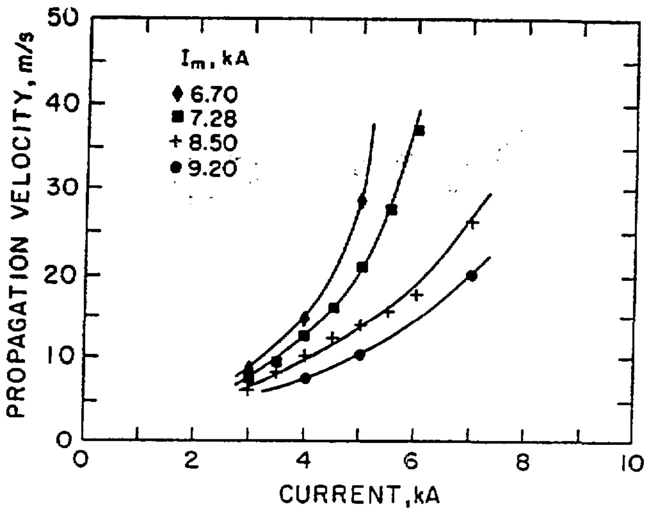

Figure 2. Longitudinal quench velocity of a number of developmental cables measured at 5 Tesla.

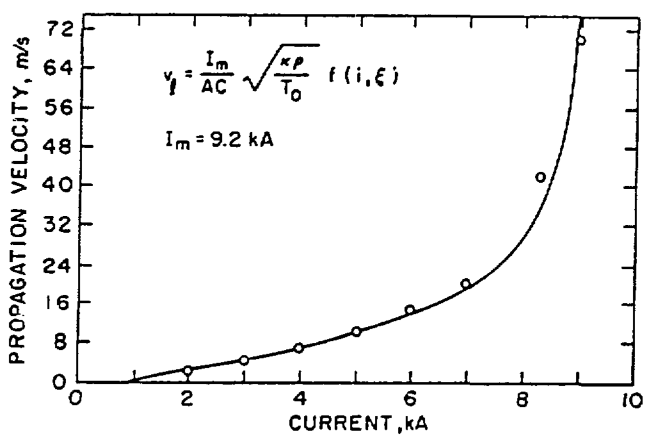

Figure. 3. Longitudinal velocity, comparison of experimental measurements with theoretical expression.

Transverse Velocity

The velocity of quench propagation from turn-to-turn is closely related to the longitudinal velocity [4] and for a specific conductor and insulator configuration can be represented by a universal curve. In Fig. 4 the turn-to-turn transit time (i.e. the inverse of the transverse velocity) is plotted against the longitudinal velocity for the "outer" and, "inner" SSC conductors. The fact that the cables differ by 40% in Superconductor content and have a correspondingly large difference in critical current is taken into account by the propagation velocity. Thus under any field-current conditions which give 10 m/s (i.e. 6000 A at 5T or 7500A at 4T for inner conductor: 5000 A at 5T or 6200 A at 4T for outer conductor) the turn-to-turn transit time will be 30 mS.

The universal nature of the turn-to-turn transit time vs. longitudinal velocity makes it easy to represent the effect of discontinuities in the windings such as the insulated copper wedges used to shape the field in the SSC dipoles.

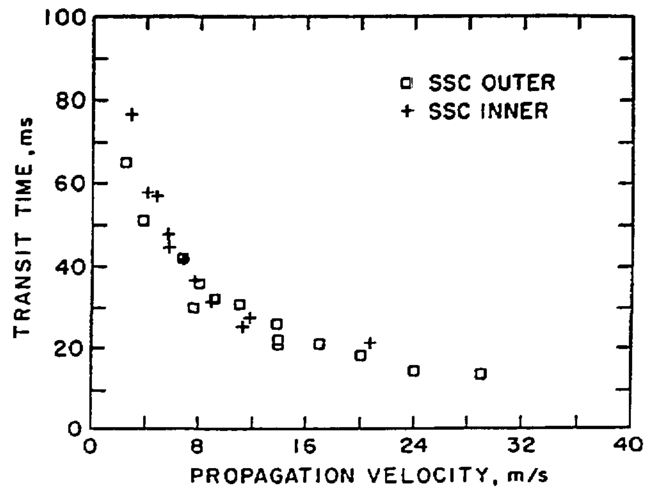

Figure 4. Turn-to-turn transit time plotted against longitudinal velocity for SSC "inner" and "outer" cables.

Propagation Across Wedges

The effect of wedges in the windings is summarized in Fig. 5 where the transit time is plotted against longitudinal velocity. The wedges of mean

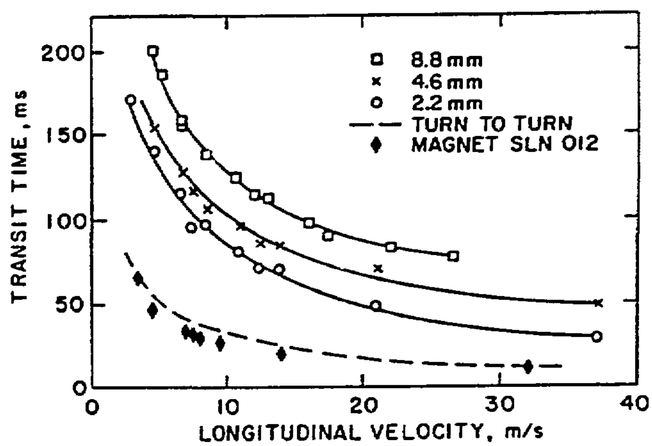

Figure 5. Turn-to-turn transit time for conductors separated by copper wedges.

thickness 4.6 mm and 2.2 mm are used in the SSC dipoles, while the 8.8 mm wedge represents an extreme case used in model magnets for the RHIC project. For reference the "universal" curve of Fig. 4 is represented by the dashed line in Fig. 5 and actual transit time vs. velocity measurements from a model dipole are included.[5] The turn-to-turn propagation is slightly faster in the magnet due to higher preloading.

While the initial values of both transverse and longitudinal velocity in a magnet are in good agreement with those measured in the simulated windings, quench "speed-up" is always observed in magnets, so that calculations of resistance buildup with time based on initial conditions represents a "worst case" situation.

If the contribution to the transit time due to the normal turn-to-turn propagation (i.e. the universal curve of Fig. 4) is subtracted from the wedge data the result represents the time delay due to the wedge and its insulation only. (See Fig. 6.

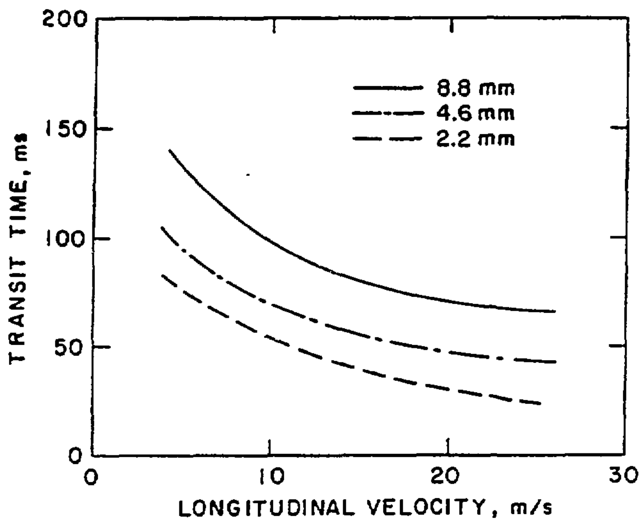

Figure 6. Transit time due to insulated wedge only.

Figure 7 is a plot of wedge delay time against the mean thickness of the wedge for specific values of the longitudinal velocity. Extrapolation to zero wedge thickness gives the delay time due to the Kapton and fiberglass insulation. This extrapolated value equals one turn-to-turn delay time as it should since the wedge insulation is identical to that used on the conductor. The linearity of the transit time vs. thickness plot implies that the heat capacity of the wedge determines the delay time and that for copper, the thermal conductivity is sufficiently high that the wedge heats uniformly. The delay time can be viewed as the time required to heat the copper in the wedge from the bath temperature up to the critical temperature of the conductor at a power level set by the transport current and the normal state resistivity of the conductor.

Magnet Calculations

The development of resistance in a magnet coil can in principle be calculated if the maximum current, I_m, and the normal state resistance are known as a function of field. The initial longitudinal velocity for a given set of boundary conditions (magnet current, point of origin of quench) can be determined from the equation in Fig. 3. The turn-to-turn propagation time is then obtained from the curve of Fig. 4 and the effect of any wedges taken into account by reference to Fig. 7. The transit time between two turns separated by a wedge is given by;

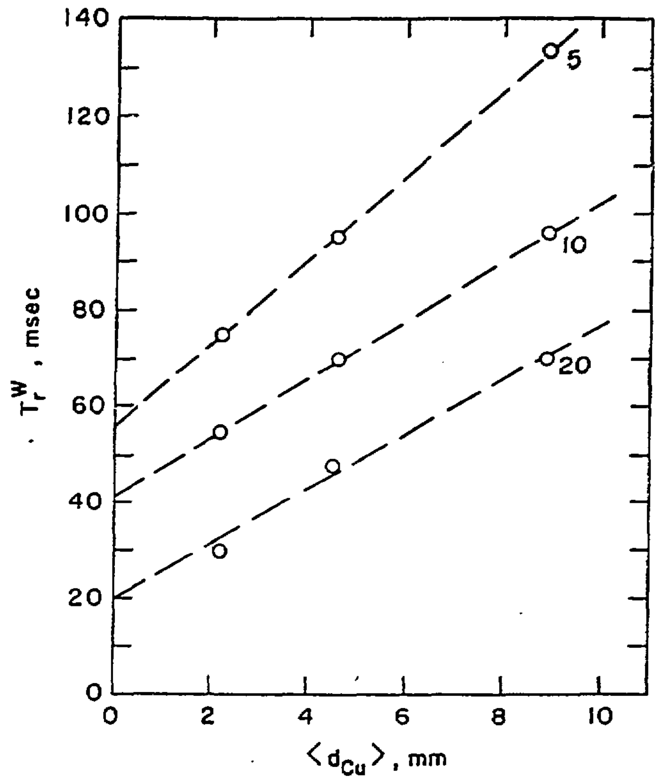

Figure 7. Wedge transit time plotted against mean wedge thickness.

$$T = 2\Delta T + B \langle d_{cu} \rangle$$

where ΔT is the normal turn-to-turn time, $\langle d_{cu} \rangle$ is the mean wedge thickness and B is the delay time per unit thickness and is a function of the longitudinal velocity. (i.e. 7mS/mm at 10 m/S). By adding the resistance of each turn as it goes normal with the appropriate time delay the coil resistance can be estimated as a function of time. While this technique cannot be extended much beyond the first hundred mS of a quench since the normal front tends to accelerate, it can be useful for estimating the relative merits of a specific arrangement of turns and wedges in a coil design.

It should be pointed out that the inverse of the procedure described above can be used to determine the point of origin of a spontaneous quench in a magnet. If the quench detection scheme provides a difference voltage between coil halves the slope of voltage vs. time and the time to the first voltage discontinuity can be used to give the normal state resistivity at the point of origin of the quench. Since this resistance is field dependent and the average field over a conductor is determined by its azimuthal position, the turn where the quench began can be located and used for diagnostic purposes.

Conclusions

Direct measurements on the propagation of a normal zone between conductors separated by a copper wedge leads to the following conclusions;

i. For a given conductor and insulation system, the longitudinal quench velocity and the transverse propagation time are related by a simple curve independent of current and field.

ii. For wedges made from metal of high thermal conductivity such as copper, the delay in quench propagation is linear with mean wedge thickness.

iii. The wedge insulation is equivalent to one normal turn-to-turn transit time.

iv. If the maximum current that the conductor will carry is know, the quench propagation throughout the windings can be estimated with

v. Excess current capability not actually achievable in a magnet due to mechanical limitations will adversely effect quench propagation since both longitudinal and transverse velocities are strongly dependent on the performance potential of the conductor.

Acknowledgments

The authors would like to thank J. A. D'Ambra for his help with the experimental details and Dr. A. G. Prodell for the turn-to-turn transit times measured in SSC model magnets.

References

1. P. F. Dahl et al., these proceedings p. (paper LF-3).
2. V. E. Keilin et al. "Les Champs Magnetiques Intenses" Paris CNRS p. 231 (1967).
3. M. Q. Barton, ISA Tech. Note # 203 BNL (1979).
4. J. D. Jackson, ISA Tech. Note #234 BNL (1980).
5. G. Ganetis and A. G. Prodell, these proceedings p. (paper LB-5).

Conclusions

Direct measurements on the propagation of a normal zone between conductors separated by a copper wedge leads to the following conclusions;

i. For a given conductor and insulation system, the longitudinal quench velocity and the transverse propagation time are related by a simple curve independent of current and field.

ii. For wedges made from metal of high thermal conductivity such as copper, the delay in quench propagation is linear with mean wedge thickness.

iii. The wedge insulation is equivalent to one normal turn-to-turn transit time.

iv. If the maximum current that the conductor will carry is know, the quench propagation throughout the windings can be estimated with

v. Excess current capability not actually achievable in a magnet due to mechanical limitations will adversely effect quench propagation since both longitudinal and transverse velocities are strongly dependent on the performance potential of the conductor.

Acknowledgments

The authors would like to thank J. A. D'Ambra for his help with the experimental details and Dr. A. G. Prodell for the turn-to-turn transit times measured in SSC model magnets.

References

1. P. F. Dahl et al., these proceedings p. (paper LF-3).
2. V. E. Keilin et al. "Les Champs Magnetiques Intenses" Paris CNRS p. 231 (1967).
3. M. Q. Barton, ISA Tech. Note # 203 BNL (1979).
4. J. D. Jackson, ISA Tech. Note #234 BNL (1980).
5. G. Ganetis and A. G. Prodell, these proceedings p. (paper LB-5).

If the contribution to the transit time due to the normal turn-to-turn propagation (i.e. the universal curve of Fig. 4) is subtracted from the wedge data the result represents the time delay due to the wedge and its insulation only. (See Fig. 6.

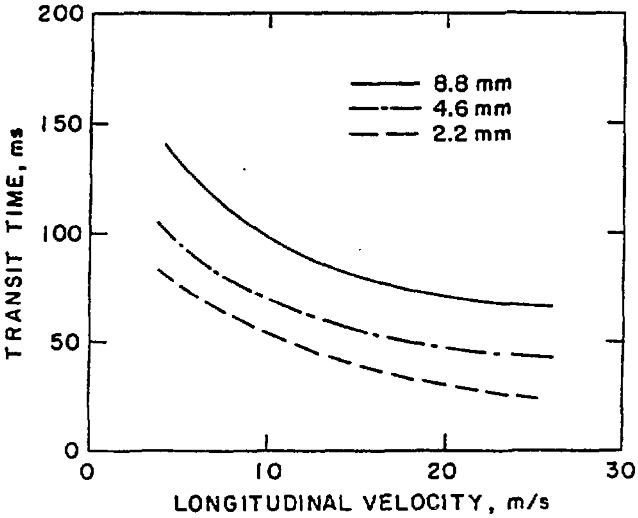

Figure 6. Transit time due to insulated wedge only.

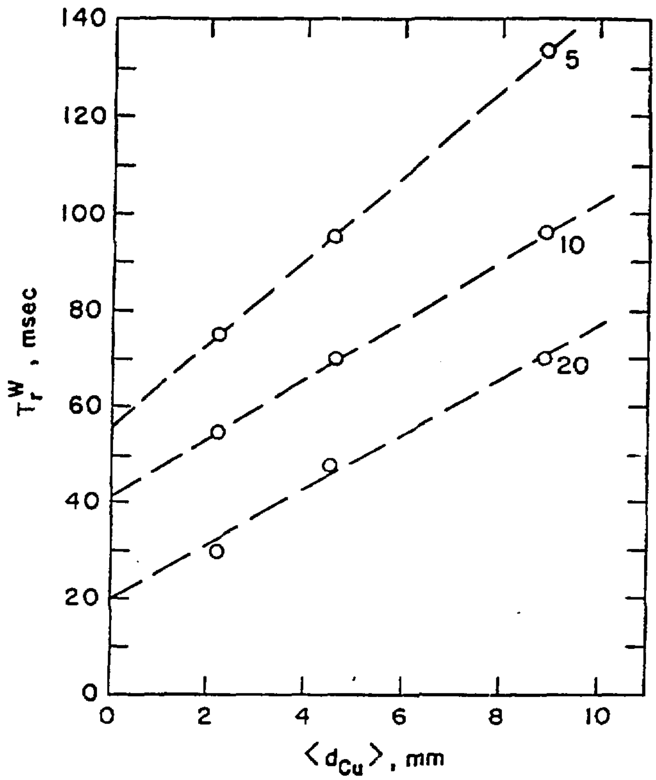

Figure 7. Wedge transit time plotted against mean wedge thickness.

Figure 7 is a plot of wedge delay time against the mean thickness of the wedge for specific values of the longitudinal velocity. Extrapolation to zero wedge thickness gives the delay time due to the Kapton and fiberglass insulation. This extrapolated value equals one turn-to-turn delay time as it should since the wedge insulation is identical to that used on the conductor. The linearity of the transit time vs. thickness plot implies that the heat capacity of the wedge determines the delay time and that for copper, the thermal conductivity is sufficiently high that the wedge heats uniformly. The delay time can be viewed as the time required to heat the copper in the wedge from the bath temperature up to the critical temperature of the conductor at a power level set by the transport current and the normal state resistivity of the conductor.

Magnet Calculations

The development of resistance in a magnet coil can in principle be calculated if the maximum current, I_m, and the normal state resistance are known as a function of field. The initial longitudinal velocity for a given set of boundary conditions (magnet current, point of origin of quench) can be determined from the equation in Fig. 3. The turn-to-turn propagation time is then obtained from the curve of Fig. 4 and the effect of any wedges taken into account by reference to Fig. 7. The transit time between two turns separated by a wedge is given by;

$$T = 2\Delta T + B \langle d_{cu} \rangle$$

where ΔT is the normal turn-to-turn time, $\langle d_{cu} \rangle$ is the mean wedge thickness and B is the delay time per unit thickness and is a function of the longitudinal velocity. (i.e. 7mS/mm at 10 m/S). By adding the resistance of each turn as it goes normal with the appropriate time delay the coil resistance can be estimated as a function of time. While this technique cannot be extended much beyond the first hundred mS of a quench since the normal front tends to accelerate, it can be useful for estimating the relative merits of a specific arrangement of turns and wedges in a coil design.

It should be pointed out that the inverse of the procedure described above can be used to determine the point of origin of a spontaneous quench in a magnet. If the quench detection scheme provides a difference voltage between coil halves the slope of voltage vs. time and the time to the first voltage discontinuity can be used to give the normal state resistivity at the point of origin of the quench. Since this resistance is field dependent and the average field over a conductor is determined by its azimuthal position, the turn where the quench began can be located and used for diagnostic purposes.