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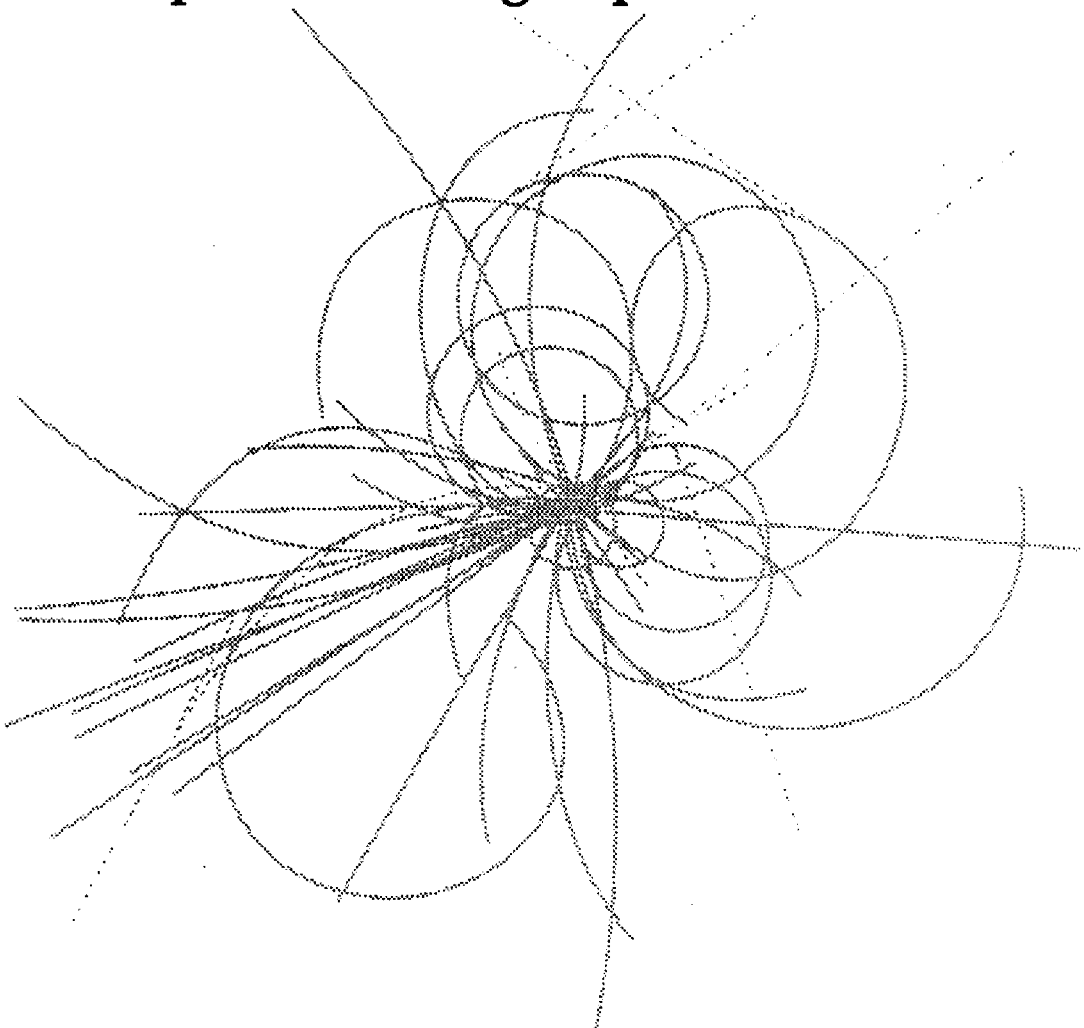

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ABSTRACT

Several 17-meter-long SSC R&D dipole magnets, instrumented with numerous voltage taps on the inner quarter coils, have been tested. These magnets, protected with quench heaters, differed in mechanical details as well as in the cables used for the winding. The voltage taps enabled us to measure longitudinal and azimuthal quench propagation velocities. Summary plots of these velocities are presented showing that, even though the Fourier conduction model doesn't apply, the mechanism of the quench is reproducible from magnet to magnet. Correlations are established between the velocities and the fraction of short sample. After showing that for currents higher than 5000 A the magnet is self-protected, we investigate the relation between the number of MIITs and the quench characteristics.

INTRODUCTION

One of the main concerns when building a 17-meter-long dipole magnet is protection of its superconducting coil in case of quench: how fast will the quench propagate? How hot will the conductor get? Do we need a protection heater to accelerate the quench propagation? Do we need an external resistor to dump part of the stored energy?

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The key element of the protection problem is the so-called *hot-spot* temperature, the temperature of the conductor at the point where the quench originated, where the rise will be the highest. The hot-spot temperature has to be limited to avoid failure of the Kapton insulation and degradation of the superconductor critical current. These effects both occur at a temperature of about 1000 K,[1] and the SSC dipole prototypes are currently operated with a maximum allowance of 800 K. A good idea of the temperature rise during a quench is given by assuming a local adiabaticity of the conductor near the hot-spot. Integrating the heat balance equation then yields[2]

$$S^2 \int_{T_0}^{T_{max}} dT \, \frac{C(T)}{\rho(T)} = \int_0^{\infty} dt \, I^2(t) \quad , \tag{1}$$

where C is the specific heat per unit volume of conductor, ρ is the conductor resistivity, S is the conductor cross-sectional area, I is the current, T_0 is the coil temperature before quench, and T_{max} is the hot-spot temperature. T_{max} is thus related to the integral over the time of the current squared. This integral, divided by 10^6, is the *MIITs integral*. Limiting the temperature rise is thus equivalent to limiting the number of MIITs, which, in turn, is determined by the current decay.

In the actual setup of the SSC magnet test area at Fermilab,[3] the magnet prototypes are discharged on themselves, without external resistors. When a quench is detected, the power supply is instantaneously phased back, and, about 40 milliseconds later, the coil leads are shorted. The current decay is thus

$$I(t) = I_0 \exp\left(- \frac{1}{L} \int_0^t ds \, \left(R_L(s) + R_c(s) \right) \right) \quad , \tag{2}$$

where I_0 is the current at quench, L is the coil inductance, R_L is the resistance of the leads, and R is the normal resistance developing in the coil. At room temperature, R_L is of the order of 40 mΩ when R_c is of about 6.5 Ω; during a quench, the leads' resistance thus becomes negligible before R. It then appears that the current decay is governed by the development of the quench through the coil.

To be able to answer the questions concerning magnet safety and especially concerning the temperature rise in case of a quench, it is necessary to study the quench development characteristics. This leads us to another set of questions, which will constitute the main focus of this paper: does the quench develop erratically or does it follow reproducible (and even predictable) laws? If such laws exist, what are the parameters influencing them and what can we do, if anything, to get safe magnets?

QUENCH DEVELOPMENT CHARACTERISTICS

The Three Axes of Propagation

The coil in a SSC dipole magnet consists of four separately wound parts joined during assembly: two inner (upper and lower) and two outer (upper and lower) quarter coils. Figure 1 shows a cross section of a Brookhaven design dipole coil.[4] The inner quarter coils have 16 turns and three copper wedges; the outer quarter coils have 20 turns and one copper wedge. (Turns are counted starting from the midplane of the coil.) In this geometrical configuration, the quench can propagate in three directions: 1) axially (or longitudinally) along the conductors, 2) azimuthally (or transversely) to conductor in the same layer, through the insulation between conductors, and 3) radially, from one layer of conductors to another, through the insulation between the two layers. Thus, the development of a quench is really a three-dimensional problem, and each propagation axis has to be investigated to understand the resistance build-up.

The first full-length SSC R&D dipole magnets (DD0001, DD0002, DD000X, and DD000Z) exhibited a lot of training.[5] In order to understand this training behavior, and to be able to determine where quenches originated, the next two magnets (DD0010 and DD0012) were instrumented with four voltage taps per turn of the inner quarter coils (128 taps total). The number of taps was then reduced on subsequent magnets (DD0014, DD0015, DD0017, and DD0018), where only specific turns (near the pole and the copper wedges) were instrumented. If the instrumented turns have varied from magnet to magnet, the location of the four taps on the instrumented turns has always been the same: about 40 cm inside the body of the coil, at both ends of the magnet. This breaks down each individual turn in four sections: two *end sections*, about 1 meter long, and two *straight sections*, about

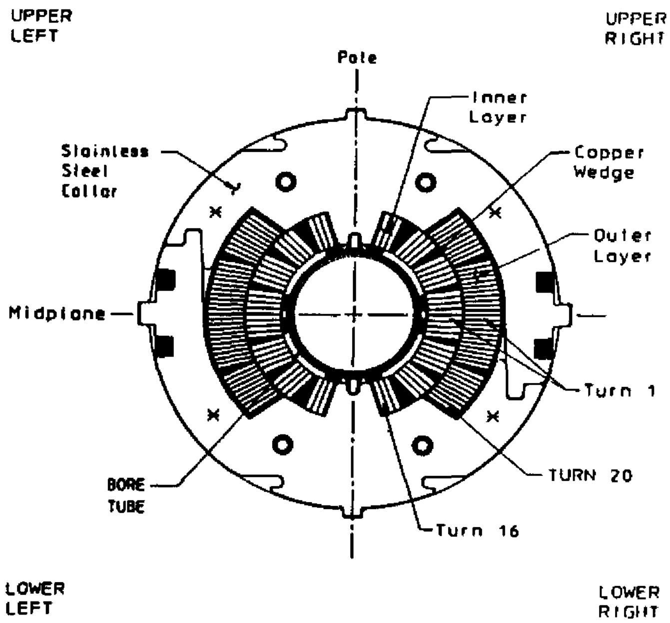

Figure 1. SSC Dipole coil cross section (C358).

15.75 meters long. This break-down of the coil in numerous sections enable us to study two propagation axes: 1) the longitudinal one, by following the quench along the straight sections, and 2) the transverse one, by looking at the time taken by the quench to reach each turn sequentially. The data reported below concern the quench testing at 4.35 K of magnets DD0010 through DD0018. The characteristics of the inner-layer cables wound in these magnets are presented in Table I. Details on their features and complete reports on their test results can be found in References 6 and 7.

Longitudinal Propagation

The longitudinal propagation has classically been described as a strictly thermal phenomenon, occurring near the transition front, where a fraction of the power dissipated in the normal zone is transmitted by Fourier conduction along the conductor to the superconducting zone, which in turn heats up and goes into transition. A quench quickly reaches an asymptotic mode, which shifts with a constant velocity. Various formulas can be found for the velocity, all relying on the Fourier conduction model, but taking into account various corrections.[2,8]

We have already reported data from magnet DD0010.[9] It appeared that the measured velocities were 3 to 4 times higher than the upper values predicted by the existing Fourier conduction models. Such discrepancy cannot be explained by uncertainties about the material properties; it must be the Fourier conduction model itself that has to be discussed or even rejected. Another mechanism is presumably involved that speeds up the propagation. One possibility could be the effect of a thermal hydraulic quench-back, as described in Reference 10, the phenomenon taking place in the helium channel between the bore tube and the coil (see Figure 1). One can also argue that, for such velocities, the current redistribution through the copper matrix of the conductor becomes long compared with the thermal propagation phenomenon, so that only a fraction of the copper has to be taken into account for calculating the velocity, in a process similar to that seen for the superstabilized conductor.[11]

Table I. Selected Parameters of Inner Layer Cables*

Magnet	DD0010	DD0012	DD0014	DD0015	DD0017	DD0018
Filament diameter (μm)	6	20	4.70	4.70	9.0	6.0
Copper to niobium-titanium ratio	1.41	1.6	1.24	1.24	1.59	1.42
Copper RRR (between 10 and 295 K)	64	79	112	120	70	69
Critical current at 5 T and 4.22 K (A)	13,170	10,760	13,380	13,710	12,848	13,284

*All cables have 23 strands that are 0.808 mm in diameter.

Since more magnets have now been tested, using different cables and test stands, it is interesting to see how the velocities evolve. Also, from a bigger statistical sample, we can hope to be able to establish empirical laws, which should give us new insights on the propagation mechanism. However, it should be noted that we have limited our investigations to quenches originating in the inner quarter coils, at a nominal temperature of 4.35 K. We only consider the velocities measured along the straight section of the side of the turn where the quench occurred. The velocities are estimated using the *time of flight technique* which involve dividing the total length of the straight section by the overall time needed by the quench to propagate along the whole section. The method is thoroughly described in Reference 9.

In Figure 2, longitudinal velocities for different magnets are plotted versus fraction of short sample; the short sample current is calculated for the turn where the quench originated using the NbTi critical-surface fit of Reference 12. It appears that the velocities for all the magnets but DD0012 lie, with a reasonable dispersion, on the same curve. The only obvious particularity of DD0012 is the size of the superconductive filaments (20 microns compared to 9 microns for the other magnets). One can also argue that DD0012 has been the only one among the long magnets to have operated above short-sample and that raises suspicions about the measurements of the critical current at 5 T and 4.22 K reported on Table I and used in the calculations. The fairly good correlation found in Figure 2 is reassuring. It indicates that, even though we don't understand the high values of these velocities (between 75 and 250 m/sec), the quench development mechanism is not erratic and seems to be reproducible from magnet to magnet, depending only on the fraction of short sample. The shape of the correlation is also reassuring, since the velocity seems to tend toward infinity when the fraction of short sample tends toward 1, i.e., when the current in the coil reaches the critical current. At this point, it would have been nice to equate this dependence of the propagation velocity on the fraction of short sample, but neither a polynomial nor an exponential can fit the data. The nature of this curve has yet to be found, but the numerical values in Figure 2 can already be used with confidence as values for other calculations.

Azimuthal Propagation

In the classical model of quench development,[2] transverse propagation is described as following a mechanism of Fourier conduction similar to the one used for longitudinal propagation, except that the thermal conductivity along the conductor, $k_{\parallel}$, was replaced by the transverse thermal conductivity along the given direction, $k_{\perp}$. A transverse propagation velocity, $v_{\perp}$, was then defined, whose ratio to the the longitudinal velocity, $v_{\parallel}$ was supposed to be equal to

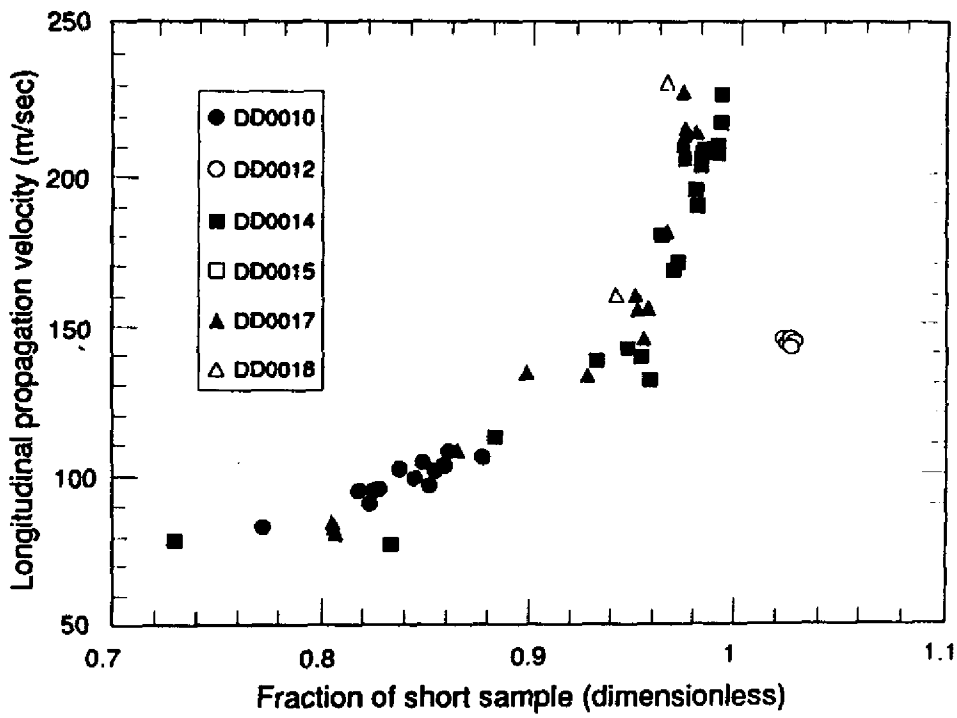

Figure 2. Longitudinal propagation velocity versus fraction of short sample.

$$\frac{v_\perp}{v_\parallel} = \sqrt{\frac{k_\perp}{k_\parallel}} \ . \qquad (3)$$

We have already detailed in a previous paper the characteristics of the transverse propagation through the inner quarter coils of magnet DD0012.[13] This is a very confusing picture, especially propagation through the copper wedges. In a model relying exclusively on the Fourier conduction, the turns on both sides of a wedge are separated by a larger thermal resistance than two adjacent turns inside a block. The propagation time across a wedge is then expected to be longer than the turn-to-turn propagation time within a block, and it should depend on the width of the wedge.[14,15] In some of the cases, we saw just the opposite: the through-wedge time was shorter than the turn-to-turn time. We once again concluded that another mechanism, different from the Fourier conduction, was involved, helping to carry the quench through the coil.

Since we cannot make sense of the details of the turn-to-turn propagation, another approach is to consider the overall time needed for the quench to propagate transversally through the 16 turns (or most of the 16 turns) of the inner quarter coils. By taking the average, we hope to erase some local particularities and get a better picture of the transverse propagation. We can also, as we did for the longitudinal propagation, reproduce the analysis on all the available long magnet data, trying to establish an empirical law. The same cautions, of course, apply in selecting the quenches: our investigation is limited to the ones already considered in the previous paragraph.

For some quenches, determination of the overall transverse propagation time is straightforward. Figure 3 shows an example of quench on magnet DD0015 (at 5625 A and 4.39 K). The quench originates in turn 16 and gently propagates from turn to turn, the voltages across the different turns rising sequentially until turn 1. We then simply measure the time difference between the beginning of the rise across turn 16 and the beginning of the rise across turn 1. For some other quenches, disturbances appear in the sequence of the rising voltages, especially in the turns of the last block (turns 4 to 1). Figure 4 shows traces from a quench on magnet DD0017 (at 6627 A and 4.37 K), which also originated in turn 16. The voltages rise one after the other from turn 16 to turn 4, but the situation is more confused in the last turns. Indeed, turn 1 starts to quench about 15 milliseconds before turn 4, followed by turns 2 and 3. Turn 4 is the last one to take off. The quench has somehow reached the midplane turn of the coil before turn 4, and the quenching of the last block of turns is due to a transverse propagation initiating in turn 1 rather than to the continuation of the transverse propagation initiating in turn 16. Nevertheless, the transverse propagation from turn 16 to turn 4 seems undisturbed, and the sequence of traces looks similar to the one in Figure 3. To be consistent in our analysis, we decided, in

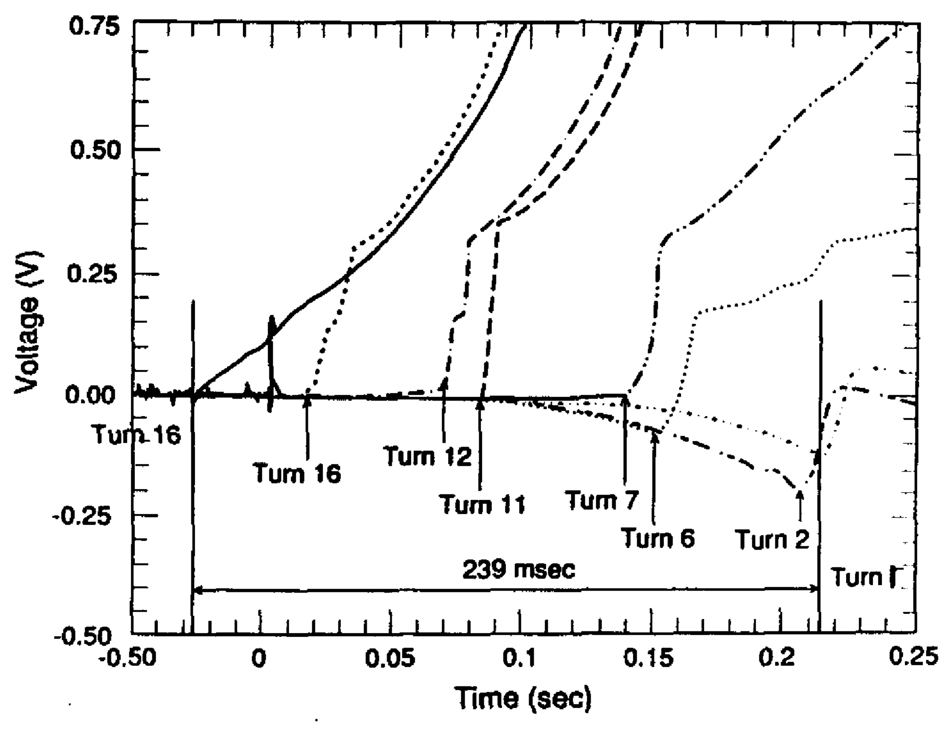

Figure 3. Example of transverse propagation through magnet DD0015 coil.

cases such as the one in Figure 4, to consider the overall propagation time between the turn where the quench occurred and the last turn rising in sequence (turn 4 in our example). (In magnet DD0010, where the quenches originate in turn 13, the time is measured between turn 13 and turn 1). An azimuthal propagation ω can then be defined as

$$\omega = n/\tau \quad , \tag{4}$$

where τ is the overall transverse propagation time and n is the number of turns involved in the determination of τ.

The azimuthal velocities for the different magnets are plotted versus the fraction of short sample in Figure 5. It appears that, as for longitudinal propagation, the velocities for all the magnets but DD0012 lie on the same curve. The dispersion is nevertheless greater than on Figure 2, especially for the fractions of short sample close to 1. As we hoped, the consideration of an average time over several turns helps to give a better picture of the transverse propagation. The conclusions that can be drawn from Figure 5 are the same as the conclusions drawn from Figure 2: even though we don't understand the details of the propagation, the quench development mechanism seems reproducible from magnet to magnet, depending only on the fraction of short sample. However, unlike the longitudinal velocities, the order of magnitude of the azimuthal velocities measured on the long magnets is comparable to the order of magnitude of the azimuthal velocities previously measured on a 4.5-meter-long SSC model dipole.[16]

Since the shapes of the correlations in Figures 2 and 5 look so similar, it is tempting to search for a relation between the longitudinal and the azimuthal velocities, in order to test Eq. (3). Figure 6 shows a plot of ω versus v_ℓ. The data can be reasonably fitted by the logarithmic curve of equation

$$\omega = 0.046\, v_\ell^{\,1.65} \quad . \tag{5}$$

It thus appears that the ratio (ω/v) does depend on the longitudinal velocity and, through it, on all kind of parameters (like the fraction of short sample), when the Fourier conduction model predicts it should be constant. This is another demonstration of this model's shortcomings. As for the longitudinal propagation, the mechanism of the quench development has yet to be found, but the data reported in Figure 5 provide a good basis for safety analyses.

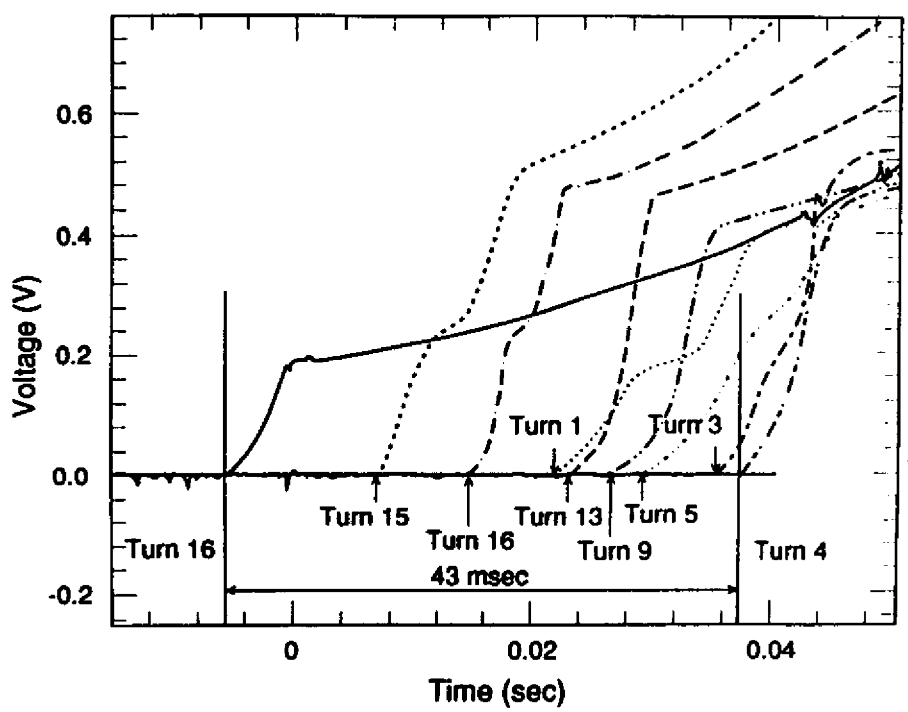

Figure 4. Example of transverse propagation through magnet DD0017 coil.

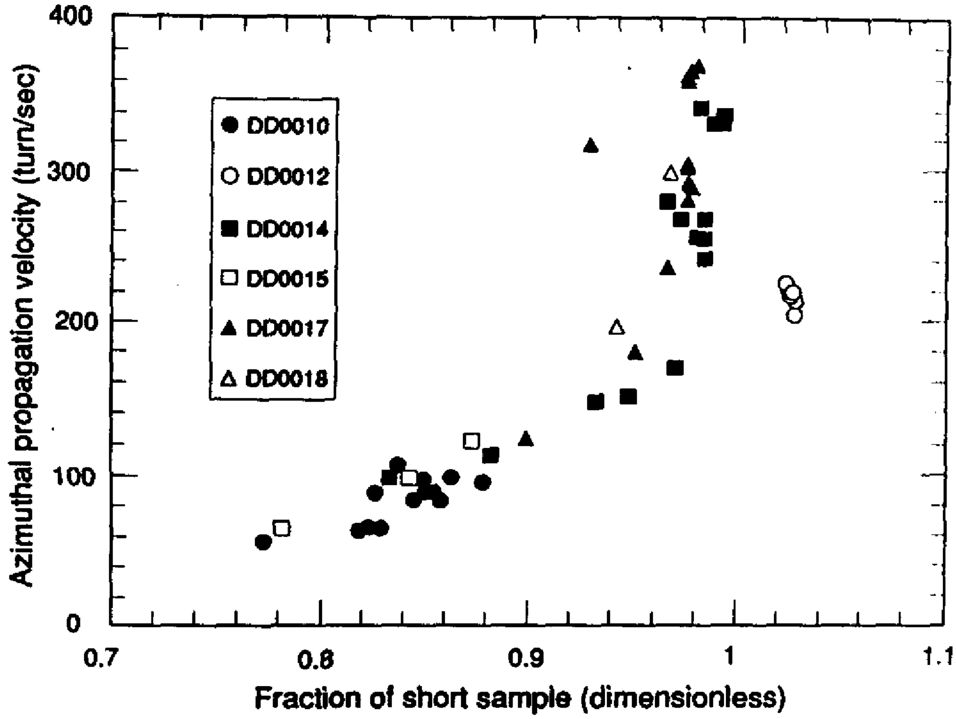

Figure 5. Azimuthal propagation velocity versus fraction of short sample.

THE MIITS ISSUE

Quench Heater Efficiency

Before starting any analysis on the MIITS we must consider the influence of the quench heaters. The long magnets are equipped with quench heaters on the outer radius of all four outer coils; the overall insulation between the heaters and the outer layer of cable is 14 mils. During the tests only two, located on diametrically opposed quarter coils, are wired. Also, in order to limit the interference with the natural development of the quench, and to allow the position of the start of the quench to be accurately pinpointed, a delay is set between the detection of the quench and the firing of the heaters. This delay has varied from magnet to magnet, from 130 milliseconds on DD0010, DD0012, and DD0014 to 80 or 60 milliseconds on more recent magnets.

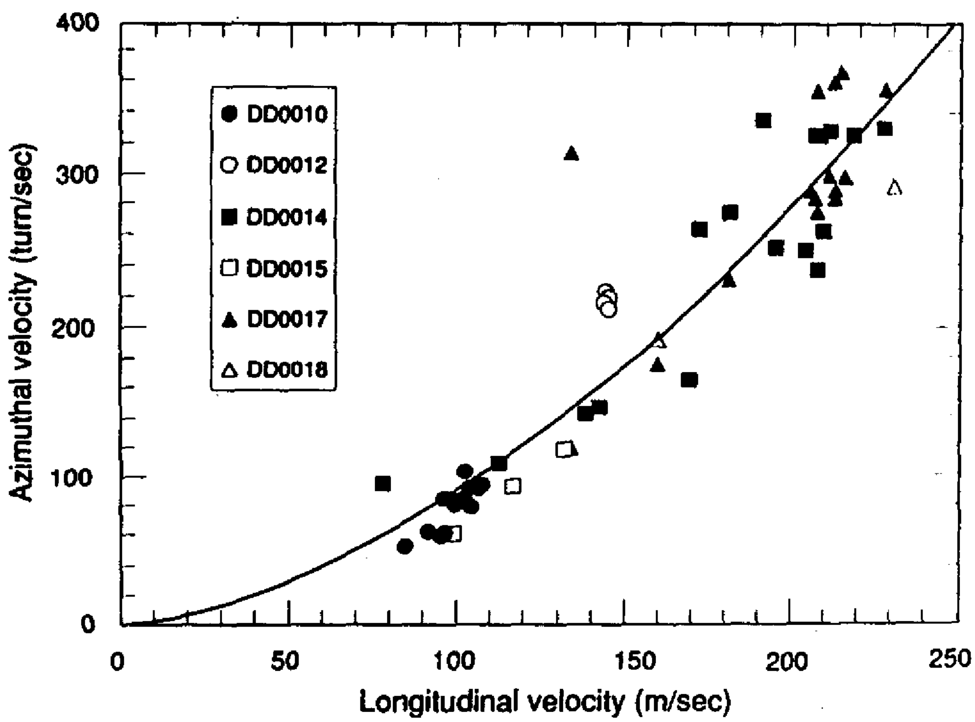

Figure 6. Correlation between azimuthal and longitudinal velocities.

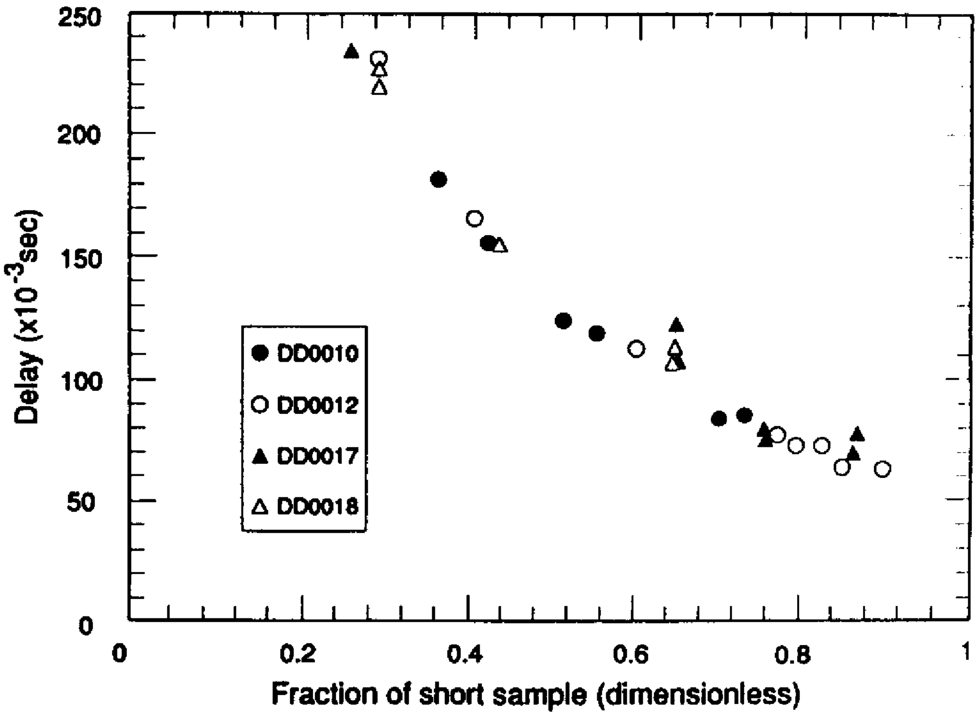

Figure 7. Delay between the firing of the heaters and the quenching of the outer coils.

Since the heaters are insulated from the conductors by a fair amount of Kapton, another delay has to be added to the one set by the operator: the time needed by the heat to cross the insulation barrier and quench the outer quarter coils. The test setup procedure for the 17-meter-long SSC dipoles at Fermilab includes manual trips at various currents. These trips consist of ramping up the magnet to a given value of current and then firing the quench heaters. Such events allow us to estimate this second delay by measuring the time difference between the heater firing and the beginning of the rise of the outer quarter coil voltages. Delays measured on the different magnets are plotted in figure 7 versus fraction of short sample; the short sample considered here is that calculated for turn 20 of the outer quarter coils.

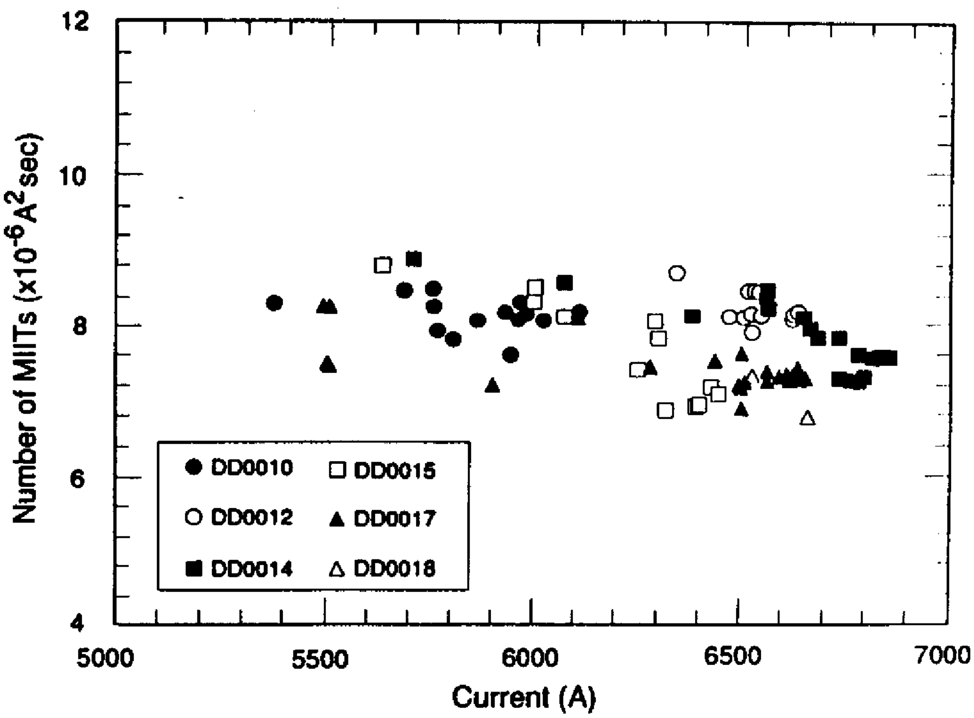

Figure 8. MIITS versus current

The data on Figure 7 lie, essentially, on the same curve. The mounting of the quench heaters is thus fairly uniform from magnet to magnet. The figure also shows that, for high currents, the delay tends toward a lower limit of 60 milliseconds. It thus appears that, once a quench has been detected, quenching of the outer coils due to the heater firing won't occur before at least 190 milliseconds for magnets DD0010 through DD0014 and at least 120 milliseconds for the recent magnets. These times have to be compared with the times needed for the quench to naturally propagate through the inner coils. The values of the velocities reported above show that, for currents higher than 5000 A, the propagation times are always smaller, i.e., that most of the natural quenching of the inner coils occurs before the heater firing has produced any effect. For the data we are dealing with, the decay of the current is thus mostly due to the natural development of the quench; the effect of the heaters is negligible.

A group of spot-heater-induced quenches on DD0017 confirms this conclusion. These quenches were initiated at a same value of current (5498 A), but the delay on the heaters was progressively increased by the operator from 0 to 100 ms. It appears that the number of MIITs rises from 7.68 to 8.72 between 0 and 60 ms and then remains fairly constant (8.81 for 100 ms). As we said, for delays set by the operator above 50-60 ms, the firing of the heaters doesn't help the propagation of the quench and has no effect on the number of MIITs.

Since firing the heaters can be delayed to a point where their influence on the number of MIITs becomes negligible, without endangering the safety of the magnet, we don't need to fire them at all. We then can conclude that for currents higher than 5000 A, the coil is self-protected. (This statement has of course to be reconsidered for lower currents, where the quench propagates much slower.)

MIITs and Quench Development

Figure 8 shows a summary plot of MIITs versus current at quench for the magnets considered so far. The picture appears very confused, which doesn't surprise us since the cables used in these magnets are very different. The analysis of the data therefore needs more thought.

The decay of the current, and thus the MIITs, is tied to the resistance build-up inside the coil, and thus to the quench development characteristics. At this point, it would be nice to verify this statement and to establish the correlation between the MIITs and the propagation velocities. From the analytical point of view, this is a nontrivial problem. In fact, the resistance growth $R_c(t)$ that appears in Eq. (2) has two terms: one is the propagation of the normal zone, but the other is the increase of the conductor's resistivity following heating. The temperature dependence of the copper resisitivity is a well-known function, but the temperature itself is not uniform through the coil and requires us to solve the heat balance equation. The best way to do that would be to re-run the program QUENCH,[2] using the velocities determined above. This, however, requires re-writing software, which hasn't been done yet.

Since an analytical approach to the problem is not now possible, we can try to establish an empirical law. The idea is to plot a time characteristic of the current decay versus a time characteristic of the propagation. Figure 9 shows the ratio of the MIITs to the current squared as a function of the inverse of the longitudinal propagation velocity. The scattered data of Figure 8 are now gently mixed, and all the magnets seem to follow the same law. The best fit of the Figure 9 data is an exponential curve of equation

$$\mathrm{MIITs} = 0.115\ 10^{-6} I_0^2 \exp\left(\frac{73.9}{v_{//}}\right) . \qquad (6)$$

To make sense of the coefficients involved in Eq. (6) probably requires a computer simulation. However, the fact that we have been able to establish such a correlation is interesting in itself, since it confirms the tight ties between the MIITs and the quench development characteristics. Also, Eq. (6) can be used as a basis for extrapolating the MIITs behavior at lower currents.

CONCLUSION

The first full-length SSC dipole magnets revealed an unexpected quench development mechanism with propagation velocities 3 to 4 times higher than seen before. After testing more magnets, we have established that this quench mechanism is reproducible from magnet to magnet. The longitudinal and and azimuthal propagation velocities depend only on the fraction of short sample, according to laws determined empirically. The true nature of this mechanism has yet to be found. A consequence of these high propagation velocities is the reasonable number of MIITs produced during a quench at high currents. Indeed, despite the length of the coil, for currents higher than 5000 A the magnets are self-protected and the protection heaters don't need to be fired. Nevertheless, further studies have to be done to see if this remains valid at lower currents.

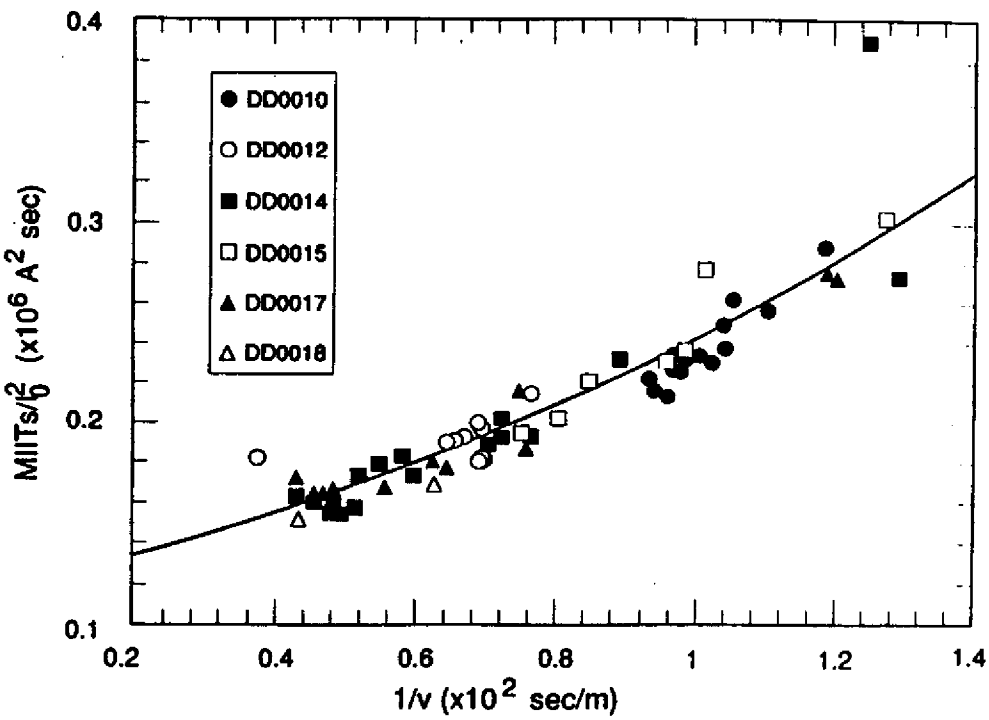

Figure 9. Correlation between MIITS and longitudinal propagation velocity.

ACKNOWLEDGMENT

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