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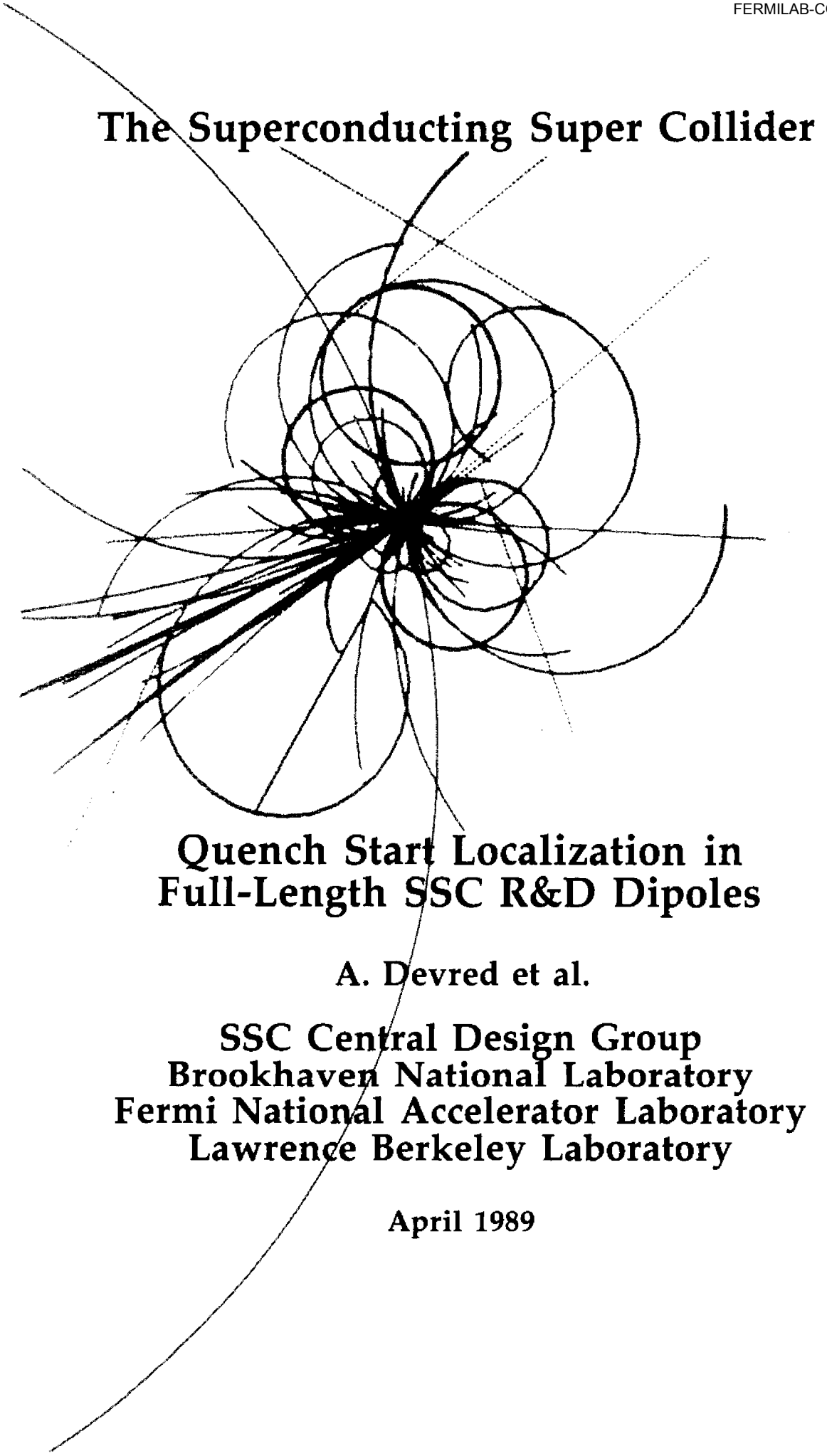

Quench Start Localization in Full-Length SSC R&D Dipoles

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"Boy! Lucius! Fast asleep? It is no matter.
Enjoy the honey-heavy dew of slumber.
Thou hast no figures nor no fantasies
Which busy care draws in the brains of men."

Julius Caesar, II. i. 229.

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ABSTRACT

Full-length SSC R&D dipole magnets instrumented with four voltage taps on each turn of the inner quarter coils have been tested. These voltage taps enable (1) accurate location of the point at which the quenches start and (2) detailed studies of quench development in the coil. Attention here is focused on localizing the quench source. After recalling the basic mechanism of a quench (why it occurs and how it propagates), the method of quench origin analysis is described: the quench propagation velocity on the turn where the quench occurs is calculated, and the quench location is then verified by reiterating the analysis on the adjacent turns. Last, the velocity value, which appears to be higher than previously measured, is discussed.

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I. INTRODUCTION

I.1. What Is A Quench?

The superconducting state only exists when materials are maintained below a temperature called the *critical temperature*. This critical temperature depends on many parameters, including the amount of current carried by the conductors and the magnetic field to which the conductors are subjected. (For a given turn of a dipole coil, the current and the magnetic field are, of course, correlated.) A three-dimensional surface, called the *critical surface*, is defined by the boundaries of critical temperature, critical magnetic field, and critical current, as shown in Figure 1. The critical surface is the very boundary between superconducting and normal resistive states.

A dipole is normally operated at conditions corresponding to a point located underneath the critical surface, where the entire coil is superconducting. Let us assume that, starting from this operating point, we ramp up the current. In ramping up the current (and thus the magnetic field) we get closer and closer to the critical surface, and soon, somewhere in the coil, we cross it. Crossing the critical surface means that, somewhere in the coil, a small volume of conductor switches to the normal resistive state. When switching to the normal resistive state, this small volume dissipates power by the Joule effect. The dissipated power then overheats the small volume of conductor and also, by thermal diffusion or another mechanism of heat-transfer, the region surrounding this small volume. If the Joule heating is sufficient, the surrounding region can then, in turn, reach the critical temperature, switch to the normal resistive state, and dissipate power. Under certain conditions, the normal region, in which the conductors have switched to the normal resistive state, can continue to grow in this manner until the coil is no longer superconducting. This process is called a *quench*.

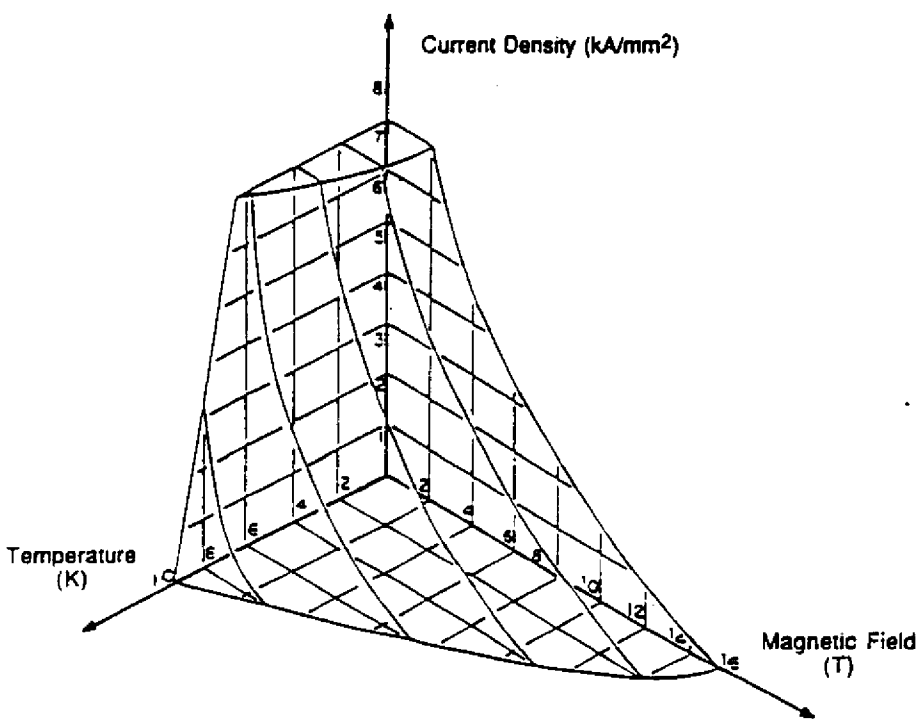

Figure 1. NbTi critical surface.

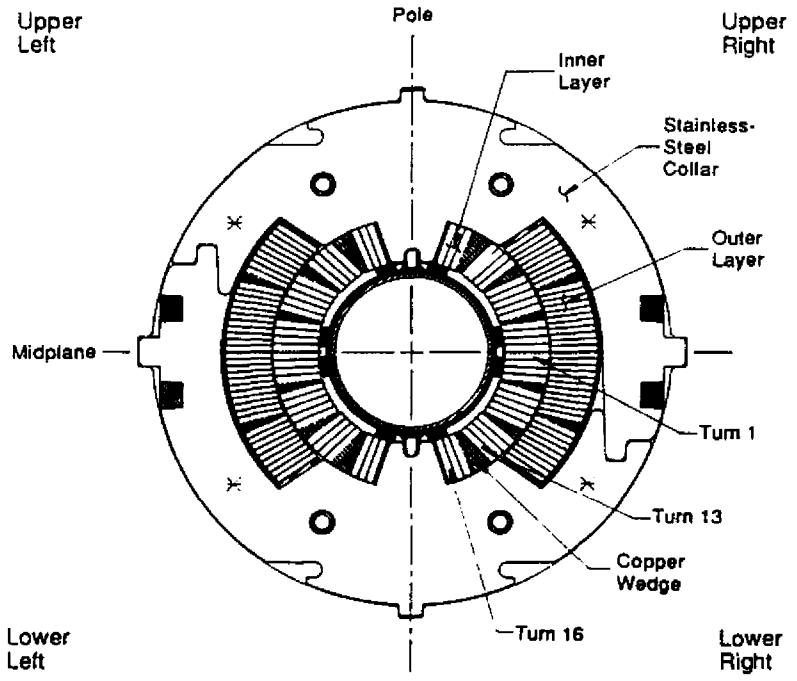

Figure 2. SSC coil cross section (C358).

I.2. Quench Origins

Quench origins can be classified in two categories: *training quenches* and *plateau quenches*. In a dipole, the turn where the conductor sees the maximum magnetic field is the pole turn of the inner coil, as shown in Figure 2. Let $B/I = f_0(I)$ designate the transfer function of this particular turn, and T_0 designate the operating temperature of the magnet. At a given temperature, the maximum value of current that can circulate in the coil is defined by the intersection, in the plane $T = T_0$, of the transfer function $B/I = f_0(I)$ with the critical surface. This maximum value is called the *short-sample current*, I_{ss}. When ramping up the current from a point located underneath the critical surface, quenches can occur at currents lower than I_{ss}. Such quenches are called *training quenches*. Quenches can also occur when the short-sample current is reached; those are called *plateau quenches*.

Plateau quenches are a consequence of the intrinsic characteristics of the conductor, and nothing can be done about them, except by improving the conductor. Training quenches are of a different nature. Since they occur at a current, I, lower than $I_{ss}(T_0)$, somewhere in the coil a volume of conductor sees a temperature increase, $T_0 + \Delta T$, such that $I = I_{ss}(T_0 + \Delta T)$. Thus, the main difference between the plateau and the training quenches is that in plateau quenches the critical surface is crossed because of an increase in current, in training quenches because of an increase in temperature. The local heating that can induce a training quench has mainly one cause in non-impregnated coils: the motion and friction of a conductor (or length of conductor) under the Lorentz force. During the quench, conductor that is not properly restrained mechanically will move. It is then possible for the conductor to lodge in a more secure position, so that in a subsequent test a higher current can be achieved. Eventually, when all the conductor is well positioned, the magnet will reach the short-sample limit. This improvement of the magnet performance is called *training*. Of course, the goal is to build magnets that will not exhibit quenches until currents are reached that are well above the operating current of the machine.

I.3. Quench Propagation Velocity

The coil in a SSC dipole magnet consists of four separately wound parts that are joined during assembly: two inner (upper and lower) and two outer (upper and lower) quarter coils. The inner quarter coils have 16 turns; the outer quarter coils have 20 turns. The turns are counted starting from the midplane of the coil. Figure 2 shows a cross section of a Brookhaven design dipole coil. In this design three copper wedges are inserted in the inner quarter coils: one between turns 4 and 5, one between turns 9 and 10, and the third between turns 13 and 14. The outer quarter coils contain only one wedge, located between turns 11 and 12. 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 in a dipole coil is really a three-dimensional problem.

Most investigations have concentrated on longitudinal propagations. In the early 1960s it was discovered[1,2] that the propagation of a quench along a conductor occurred with a constant velocity, called the *propagation velocity*. Since their discovery, these propagation velocities have been the object of numerous papers; most of them can be found in reference 3. Very few studies have been performed on transverse propagations. They are usually described as following a mechanism similar to the longitudinal propagation, except that the thermal conductivity along the conductor is replaced by the transverse thermal conductivity along the given direction.[4]

II. DETERMINING THE LOCATION OF A QUENCH

II.1. The Technique

When prototype SSC dipole magnets are tested, the current is ramped up from zero until a quench occurs. Two parameters are carefully recorded during the test: the temperature of the helium (assumed to be equal to that of the coil, with some allowance for phase lag) and the current at quench. The quench current is then compared with the estimated short-sample current at the given temperature, and the nature of the quench is identified. If it is a training quench, the next step is to determine where the quench started. Knowing where the quench originated can be very helpful to the magnet builders, because it pinpoints the mechanically weak areas of the coil that need improvement.

The question is how to accurately locate the quench origin. Because the main manifestation of a quench is the development of a resistive zone, it is logical to instrument the coil with voltage taps. To perform any clever analysis, we have to be able to discriminate among the three possible axes of propagation, so each turn of the coil is instrumented with four voltage taps, as shown in Figure 3. These four voltage taps break the turn into four sections, along which the propagation is only longitudinal. During testing, voltages across all sections of all turns are permanently recorded. As long as the coil is entirely superconducting, of course, they are nil. Once a quench has occured, they sequentially exhibit resistive voltages as the quench propagates. By determining which section shows the first resistive voltage, then estimating the propagation velocity along this particular section, we are able to locate the quench origin to within 10 cm.

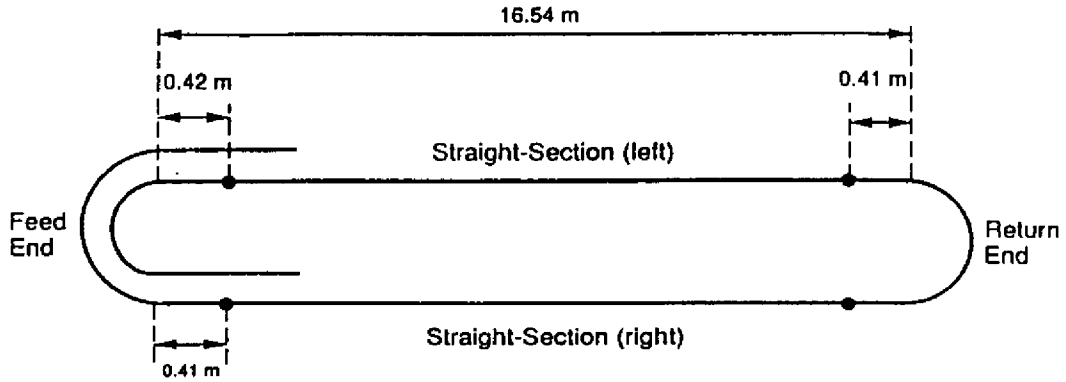

Figure 3. Tap location on turn 13 of lower inner quarter coil. (not to scale)

Of the full-length SSC dipole prototypes tested in 1988, two were equipped with four voltage taps per turn of the inner quarter coils (128 taps total): magnet DD0010 and magnet DD0012. The features of these magnets and their test results have been presented elsewhere.[5,6,7] Descriptions of the magnet test set up can also be found in references 8 and 9. As shown in Figure 3, the voltage taps were located about 40 cm inside the body of the magnet. This defines two *end sections*, about 1 meter long, and two *straight sections*, about 15.75 meters long. In our jargon, the *feed end* is the magnet end where the power leads are located, and the *return end* is the opposite end. *Right* and *left* sides are defined by facing the magnet at the feed end. We will now discuss an example of quench localization on magnet DD0010.

II.2. An Analysis Example

To illustrate our method of analysis, we have chosen a typical quench of long magnet DD0010. The characteristics of this quench are presented in Table I.

The first rising voltage shows that the quench occured in the right-hand straight section of the lower inner quarter coil on turn 13. As shown in Figure 2, turn 13 is located next to the copper wedge closest to the pole. Figure 4 shows a plot of voltages across this straight section and across the two corresponding end sections of turn 13. The quench starts somewhere in the straight section and propagates in both directions (with two fronts), toward the two end taps. After 71 milliseconds it hits the return end tap, and the voltage across the return end section takes off. In the meantime, the quench continues to propagate towards the feed end tap (with only one front) and reaches it after 84 milliseconds. At that time, the voltage across the feed end section starts to rise; the entire straight section has switched to the normal resistive state.

Table I. Selected Quench Characteristics

Temperatures			
Feed End	4.32 K	Return End	4.46 K
Pressures			
Feed End	3.99 10^5 Pa	Return End	3.98 10^5 Pa
Current at quench	5,680 A		
Estimated short-sample*	6,717 A		

* Using the return-end temperature.

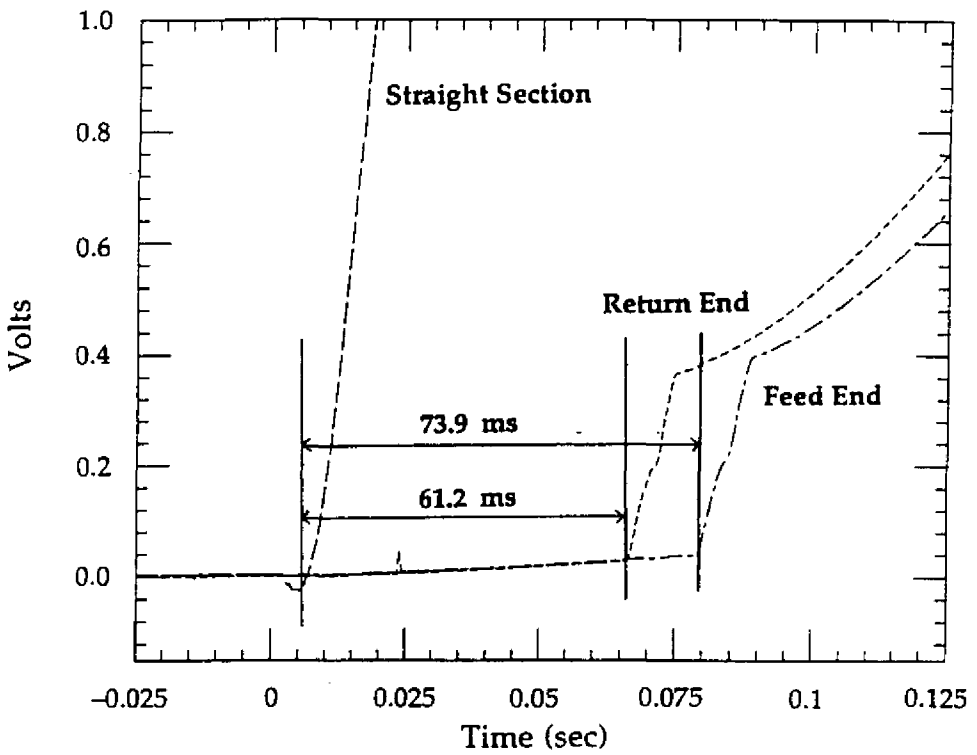

Figure 6. Quench localization on turn 12.

To propagate transversely, the quench will follow the shortest thermal path between conductors. Since the conductor insulation and the coil prestress have been made as uniform as possible along the coil, the shortest path is a straight line perpendicular to the conductors. The quench will thus start to propagate on adjacent turns at the same longitudinal location as its origin on turn 13. Verification of the quench start location on turn 13 can then be made by reiterating the quench start analysis on turns 12, 11, and 10. For example, a plot of voltages across the turn 12 right-hand straight section and across the two corresponding end sections is given in Figure 6. These traces look very similar to that of turn 13, and the propagation velocity can be calculated using the same time-of-flight technique. The results of the quench start analyses on turns 13 through 10 are presented in Table II.

Table II. Quench Start Analyses on Different Turns of Magnet DD0010

Turn Number	Propagation Velocity	Quench Start Location*
13	102 ms^{-1}	7.17 m
12	117 ms^{-1}	7.12 m
11	127 ms^{-1}	7.18 m
10	136 ms^{-1}	7.07 m

* The origin of the axis is the turn 13 right-hand return-end tap.

An estimation of the quench start location, L_{qs}, from the return end tap is then given by

$$L_{qs} = v\, t_1 \quad . \tag{2}$$

In our example, we have

$$L = 15.72 \text{ m} \quad .$$

It yields

$$v = 101.6 \text{ ms}^{-1} \qquad\qquad L_{qs} = 7.2 \text{ m} \quad .$$

This method for calculating the quench propagation velocity is called the *time-of-flight* technique.

II.3. Accuracy of the Time-of-Flight Technique

How accurate is this estimation of the quench origin? We do have some means to evaluate it. As we described earlier, while the quench is propagating along the conductor, it is also propagating transversely, from turn to turn, through the insulation between conductors. After a while, we expect to see the quench reach turn 12, then turn 11, and so on. Figure 5 shows a plot of the voltages across the right-hand straight sections of turns 13, 12, 11, and 10. They exhibit exactly the expected behavior. Of course, the quench is also propagating in the other direction, toward turn 14, but the copper wedge between turns 13 and 14 interposes a thermal resistance, which delays the propagation and makes the signals more difficult to interpret. This is also the case for the wedge located between turns 10 and 9.

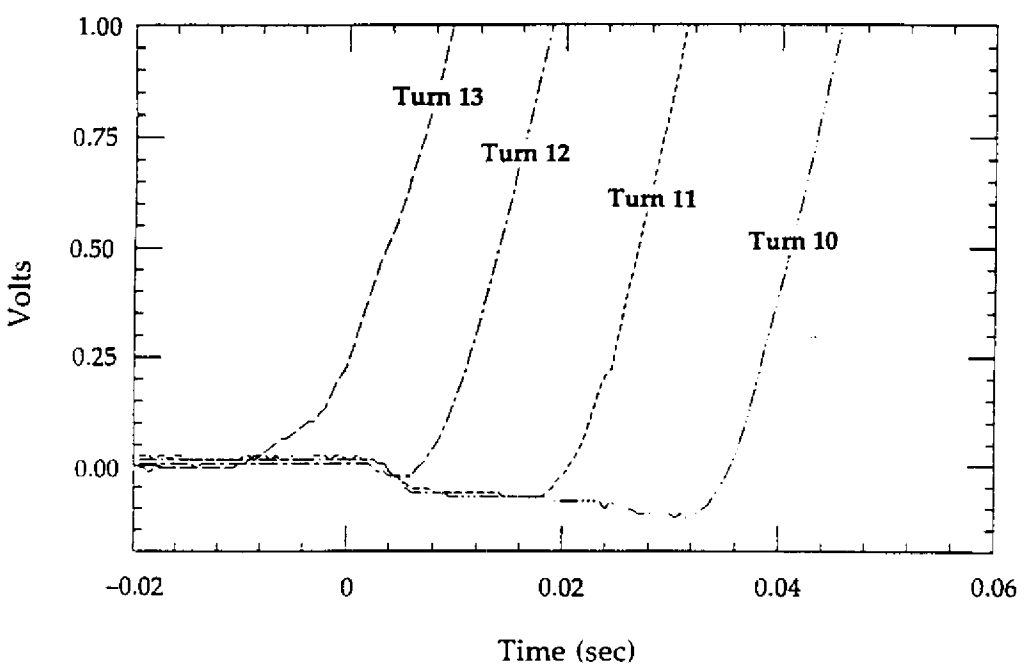

Figure 5. Transverse propagation.

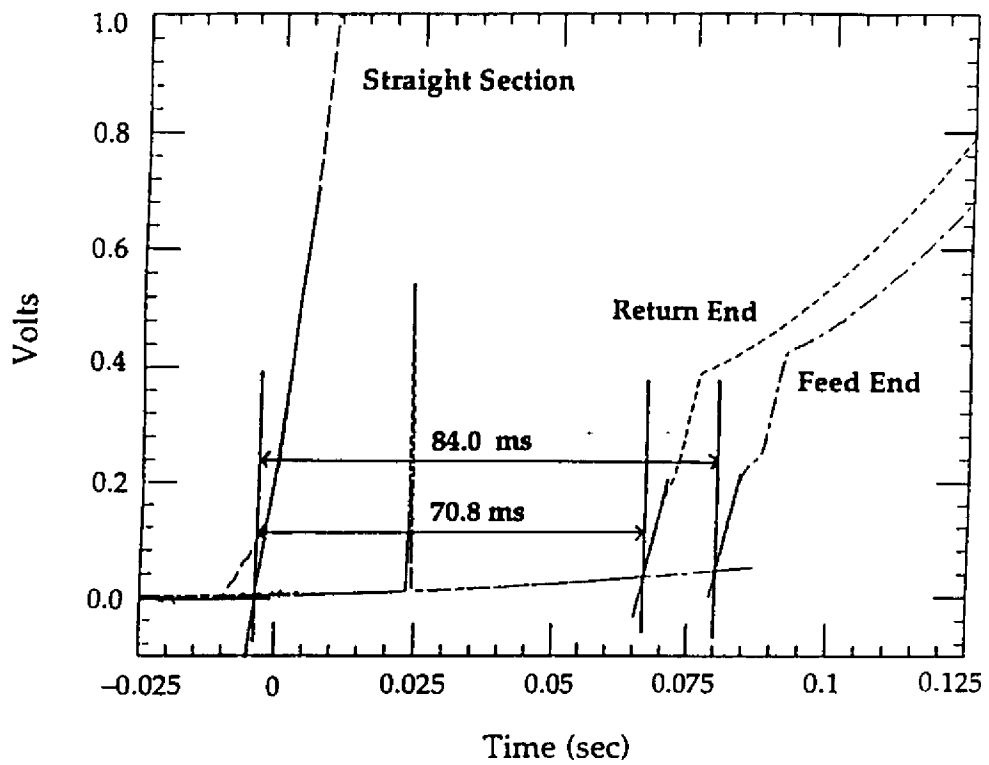

Figure 4. Quench localization on turn 13.

First of all, we want to point out that these signals, which are unfiltered and presented as recorded, are of very good quality. They reveal what is going on in amazing detail. For example, let us follow the quench when it arrives in the feed end section. This section can be geometrically divided into three parts: a straight segment of about 40 cm; a curved section of a few centimeters, where the conductor makes a U-turn; and another straight segment, on the left-hand side of the turn. From the magnetic point of view, the two straight segments are similar and see the same magnetic field as the straight section. The curved section, on the other hand, is outside the iron yoke and sees a much lower magnetic field (by a factor of 10%). We then expect to see three phases as the quench propagates along the end section: a fast propagation mode very similar to the one on the straight section, followed by a slow-down when the quench enters the low-field curved section, and then a recovery of the fast propagation mode once the quench is on the other side of the turn. This is exactly what the traces of Figure 4 show. Also, once the entire end section has switched to the normal resistive state, the voltage continues to grow, although less rapidly, due to the heating of the conductor by the Joule effect, which continuously increases the copper's resistivity.

Determination of the quench start location is rather straightforward. Let us assume that the quench propagation velocity, v, is constant along the straight section (this assumption will be verified later). If t_1 is the time difference between the starts of the straight section and the return end section voltages, and t_2 is the time difference between the starts of the straight-section and the feed-end voltages, v is given by

$$v=\frac{L}{(t_1+t_2)} \quad , \tag{1}$$

where L is the length of the straight section.

The results in Table II agree within 5 cm on turns 13, 12 and 11. The error bar grows to 10 cm with turn 10, which takes off more than 40 ms after turn 13. We consider this conservative number of 10 centimeters to be the accuracy with which we are able to longitudinally locate the quench origin. These 10 centimeters have, of course, to be compared with the 15.75 meter-long straight sections.

III. THE PUZZLE OF THE VELOCITIES

Magnet DD0010 was the first full-length SSC dipole to be equipped with so many voltage taps. One of the most unexpected results of the analysis described above was the values of the quench propagation velocities that were obtained. They are much higher than the velocities previously measured and reported in the literature,[3] for both conductor samples in specific laboratory tests and actual coils. They are even higher than the velocities measured previously on short SSC model dipoles (a 4.5-m model[10] and a 1.8-m model[11]), where they did not exceed 30 ms^{-1}, even for currents close to short sample. How can we be certain that the time-of-flight technique is reliable?

There is another method for estimating the propagation velocity: using the slope of the voltage traces when they start to rise. The beginning of the rise of any voltage trace, across any section of the coil, corresponds to the early moments of the quench propagation along the given section when no significant heating by the Joule effect has occurred that would affect the conductor's resisitivity. As long as the heating is negligible, the derivative of the voltage U across the section can then be related to the current I, considered as constant, and to the propagation velocity v by

$$\frac{dU}{dt} = \frac{\rho I}{A} n v \quad , \tag{3}$$

where ρ is the resisitivity per unit length of conductor, A is the conductor area, and n is the number of propagation fronts along the given section at the time of the slope calculation.

Once ρ and A are known, it is then easy to deduce the velocity from the voltage slope. This method of calculation is called the *derivation* technique.

The characteristics of the conductor are summarized in Table III. Of course, the resistivity value to be introduced in Formula (3) has to take into account the magnetic field effect. At the given current, the field is calculated from the transfer function $B/I = f(I)$ of the given turn. Of course, the magnetic fields do vary across the cable. For turn 13, the peak field is estimated to be given by

$$B / I = 0.9128\ 10^{-3} + \frac{0.7505}{I} \quad . \tag{4}$$

Table III. Selected DD0010 Inner Layer Cable Characteristics

Number of strands	23
Strand diameter	0.808 mm
Filament diameter	6 μm
Copper to niobium-titanium ratio	1.41
Copper RRR (between 10 and 295 K)	64
Critical current (at 5 T and 4.22 K)	12,980 A

Table IV. Turn 13 Velocities (Derivation Technique)

Section	Number of fronts	Voltage slope	Velocity
Straight right	2	84.5 Vs^{-1}	92.7 ms^{-1}
Return end	1	42.6 Vs^{-1}	93.3 ms^{-1}
Feed end	1	43.0 Vs^{-1}	92.7 ms^{-1}

Table IV shows the velocities calculated by the derivation technique at the beginning of the rise of the voltages across the turn 13 right-hand side straight section and the two corresponding ends. We first notice that the values appear to be very close to each other. This justifies, *a posteriori*, our assumption that the quench was propagating longitudinally with a constant velocity. Second, the constant value estimated by the derivation technique appears to be in fairly good agreement with the velocity estimated by the time-of-flight technique (the 10% discrepancy can easily be attributed to the uncertainties of the conductor characteristics). Thus, these two independent methods lead to the same results. The 100 ms^{-1} are then fully credible.

Another enigma appears when one considers these 100 ms^{-1} in terms of existing theories of quench propagation. In the classical description of longitudinal propagation, the "engine" of the quench is located close to the transition front, where a fraction of the power generated in the normal zone is transmitted by conduction along the conductor copper to the superconducting zone, which, in turn, heats up and goes into transition. In this model, the helium surrounding the conductor can only slow down the propagation by absorbing part of the dissipated power. An upper limit, v_0, of the velocity can then be calculated by considering a single bare conductor behaving adiabatically. Using formula (29) of reference 3, with the quench characteristics of Table I and the conductor characteristics of Table III, yields

$$v_0 = 27.6 \text{ ms}^{-1} \quad .$$

The actual propagation velocity is then almost four times higher than the upper limit predicted by the classical model. This means that another mechanism, different from the simple Fourier conduction along the copper conductor, must be speeding up the propagation. What could this be? It is too early for us to draw any conclusions; we only want to mention an interesting conjecture that can be found in reference 12.

IV. CONCLUSION

The above results demonstrate indisputably the successful use of voltage taps to test SSC R&D dipoles. Without them, we would never have been able to locate to within 10 cm the quench origin, as well azimuthally (which turn of the coil) as longitudinally (where on the turn). Nor would the unexpectedly fast quench propagation velocities of 100 ms^{-1} have come to light. Of course, magnet DD0010 has been quenched more than once. For each quench we have been able to repeat these analyses and to obtain similar, equally accurate results. The particular example we have presented here is then reproducible. In fact, the 15 quenches of magnet DD0010 were all training quenches and all occured on turn 13, either in the upper inner or the lower inner quarter coil, in either the right-hand or the left-hand straight section. The longitudinal locations also varied from quench to quench. These data revealed a global misbehavior of turn 13. When the magnet was subsequently disassembled, it was found that the copper wedges next to the turn were loose (a possible consequence of a handling error during final preparation prior to testing). The analysis of voltage tap data has given us considerable information about quench source, which has significantly strengthened the SSC dipole design.

V. ACKNOWLEDGMENT

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