SSCL-N-791

Electrical Performance Characteristics of the 40-mm Dipole String Test

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June 1992

* Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

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Abstract

There has been significant effort devoted to the development of superconducting dipole magnets required for the Superconducting Super Collider (SSC). The 40-mm aperture dipole magnet development program, a forerunner of the current 50-mm design, has provided an excellent prototypical platform to conduct magnet research and development.[1] These magnets have been thoroughly evaluated and are well understood. Less well understood are the system dynamics encountered when these magnets are configured together as an accelerator lens.

1.0 INTRODUCTION

The 40-mm dipole string test, located at Fermi National Accelerator Laboratory (FNAL), consists of five superconducting dipole magnets in a string configuration. The intent of the string test is to obtain data for model verification and information on the magnitudes of pressures and voltages encountered in a string environment. These results provide important data relevant to the Accelerator System String Test (ASST) using the 50-mm dipole magnet design. The first phase of this test is planned for completion in October 1992. This discussion presents a summary analysis of the electrical performance characteristics encountered during quench testing of the 40-mm string. The results provide an indication of how well individual magnets performed during spontaneous quenching by a single magnet, and during system quenches induced by simultaneously firing the strip heaters. Evaluation of the data illustrates the importance of maintaining consistency in the magnet design. Variations in the design between magnets used in a string configuration can have a dramatic impact on system performance.

2.0 CONFIGURATION

2.1 Method

The string is composed of five 40-mm dipole magnets that include D-0017, D-0026, D-0019, D-0027, and D-0201. After the superconducting magnets are wired together in a series configuration, they are cooled to a nominal operating temperature of 4.35 K. Figure 1 illustrates the string configuration and data acquisition system used to collect quench data. A high-current, DC power supply is used to provide a maximum of 6600 A of current to the string. An energy dump is not used with the string. The energy contained in the magnetic field of the magnets during a string quench is dissipated into the magnet windings.

Each dipole magnet consists of four superconducting coils. The differential voltage across each coil is monitored by the quench protection monitor system. There are four strip heaters for each magnet that are positioned along the length of the outer coils in a quadrant configuration. The strip heaters in opposing quadrants are connected together electrically, as illustrated in Figure 2. Each set of strip heaters is wired in a series configuration between magnets to a heater firing unit. This configuration protects the magnet by providing a level of redundancy that ensures that the outer coils quench despite a failure in one of the heater firing units (see Figure 2).

When the power supply is on and there is current in the string, the quench protection system actively monitors the coil voltages. When a voltage across a coil exceeds a predetermined threshold, the quench protection system switches the high-current power supply from the string using an Silicon Controlled Rectifier (SCR), and commands the heater firing units to discharge their stored energies into the magnet strip heaters. The power supply is phased back to zero current.

The voltages generated in each of the four coils of the five dipole magnets, along with the string current amplitude, are collected by the data acquisition system upon detection of an event that causes the strip heaters to fire. Each data acquisition channel contains a circular buffer that allows for collection of both pre- and post-event data. The data acquisition system collects data for 0.5 sec before the event and for 1.5 sec after the event at a sampling rate of 1 KHz. When a quench event is either detected or initiated, the quench protection system issues a signal that triggers the transient recorders. When the transient recorders are filled, the data acquisition system downloads the contents of the recorder memory and stores the data in a disk file for later analysis.

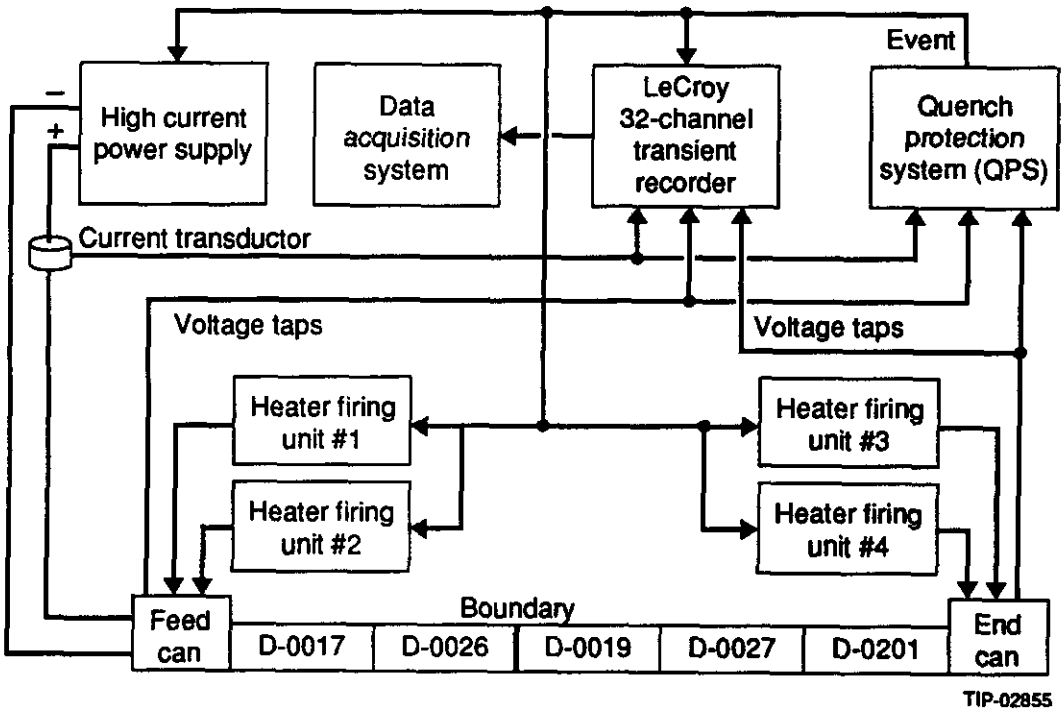

Figure 1. Functional Electrical Configuration for the String Test Conducted at FNAL.

2.2 Background

Before reviewing the data, it is important to discuss the individual characteristics of the magnets. The evaluation of experimental data also provides the necessary background for determination of the analysis requirements for the ASST. Analysis of the electrical quench data provides an opportunity to evaluate how well the superconducting dipole magnets operate when several magnets are tied together into a system. These characteristics provide a "string personality" profile that can be compared against the data when interpreting results. As illustrated in Figure 2, heater firing units #1 and #2 drive the strip heaters in D-0017 and D-0026. Heater firing units #3 and #4 drive the strip heaters in D-0019, D-0027, and D-0201. One of the strip heaters in D-0017 failed, leaving only three strip heaters functional in D-0017 and D-0026. These magnets do not quench as uniformly or as quickly as a typical magnet because less energy is deposited on the outer coils due to a larger percentage of superconducting cable in the windings.

From single magnet testing results, dipole D-0019 exhibited the smallest operating margin of any of the magnets in the string. Whenever the strip heaters were fired, D-0019 was the first magnet to propagate a quench condition. In addition, one of the voltage tap connections on D-0019 was lost during cooldown. The upper coils of D-0019 were monitored together (see Figure 4 (c)).

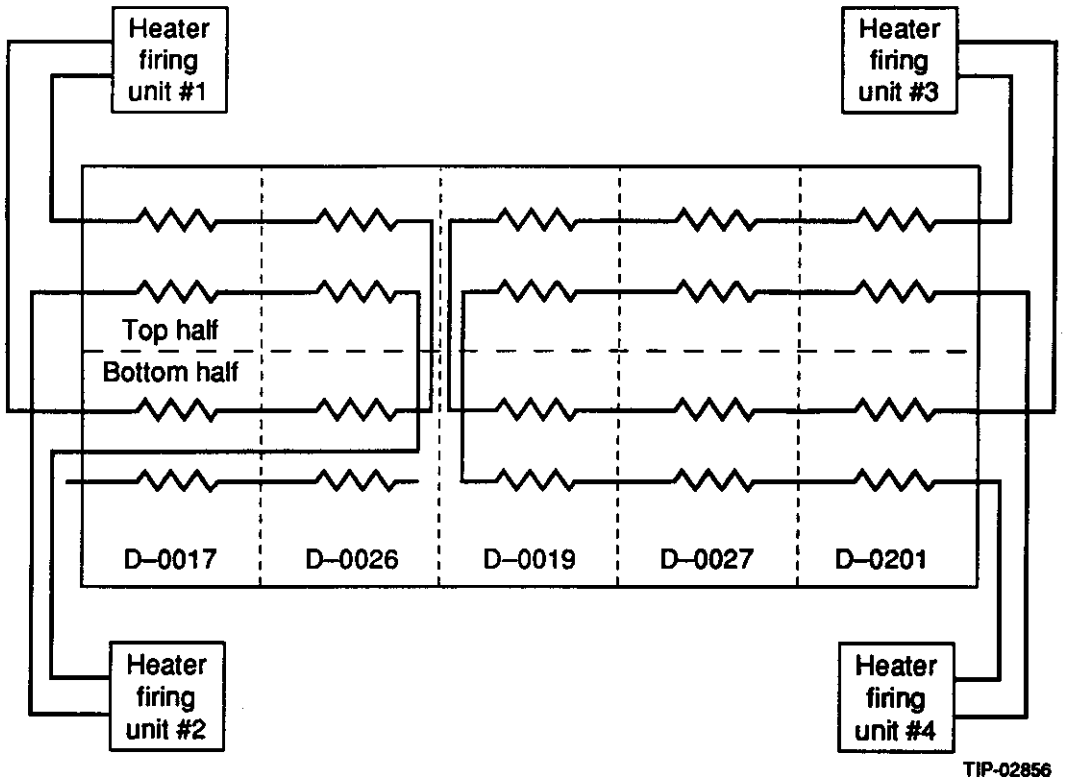

Figure 2. Strip Heater Configuration for the String Test. Note that D-0017 and D-0026 have only three strip heaters functioning.

D-0027 was unique in that nothing particularly unusual about it was noted, except for one spontaneous training quench. The end clamps on the magnet were loosened and retightened before the magnet was installed into the string. This could have caused the training quench. Magnet D-0027 can be used as the nominal benchmark magnet for comparison with the other string magnets.

The strip heaters used in D-0201 had significant design differences compared to the other magnets. More kapton insulation was used between the strip heaters and the coils. The additional insulation significantly retarded the deposition of energy from the strip heaters to the coils. Since the Brookhaven-style heaters of D-0019, D-0027, and D-0201 were tied together in series, it was not possible to tune the strip heaters in D-0201 without adversely affecting the other magnets. This meant that D-0201 would not quench as efficiently or as effectively as the other string magnets due to the longer time required for the quench to develop and propagate. The energy stored in the magnetic field of D-0201 was mostly dissipated in the other magnets during quench conditions because D-0201 did not significantly participate in the quench event.

3.0 DETAILED ANALYSIS OF A SPONTANEOUS QUENCH

Data-processing algorithms were developed to analyze and plot the string data. This section provides an in-depth analysis of a spontaneous quench on the lower outer coil of D-0027 that occurred on October 8, 1991. Figure 3 (a) plots the string current decay. Figure 3 (b) is the calculated derivative of the current decay and is necessary in calculating coil resistance. Figures 4 (a) through 4 (e) plot the resultant voltage signals from all the magnets for each coil. The coils in the graphs are referred to as Upper Inner (UI), Upper Outer (UO), Lower Inner (LI), and Lower Outer (LO). The marker at $t = 0$ is the time at which the quench protection monitor announced an event. The actual quench was detected 15 msec before the strip heaters were energized.

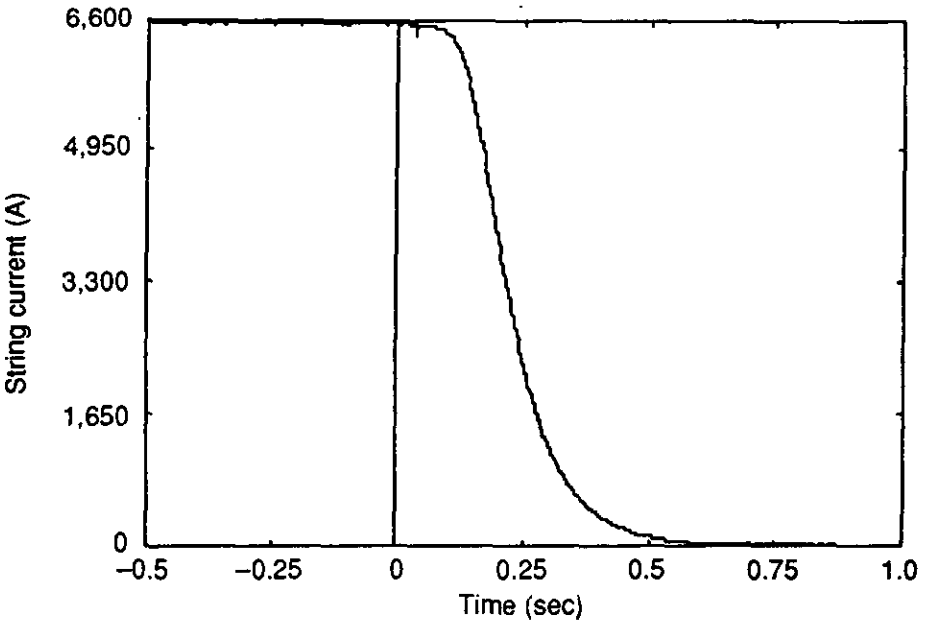

Figure 3(a). String Current *I(t)* for the Spontaneous Quench on October 8, 1991.

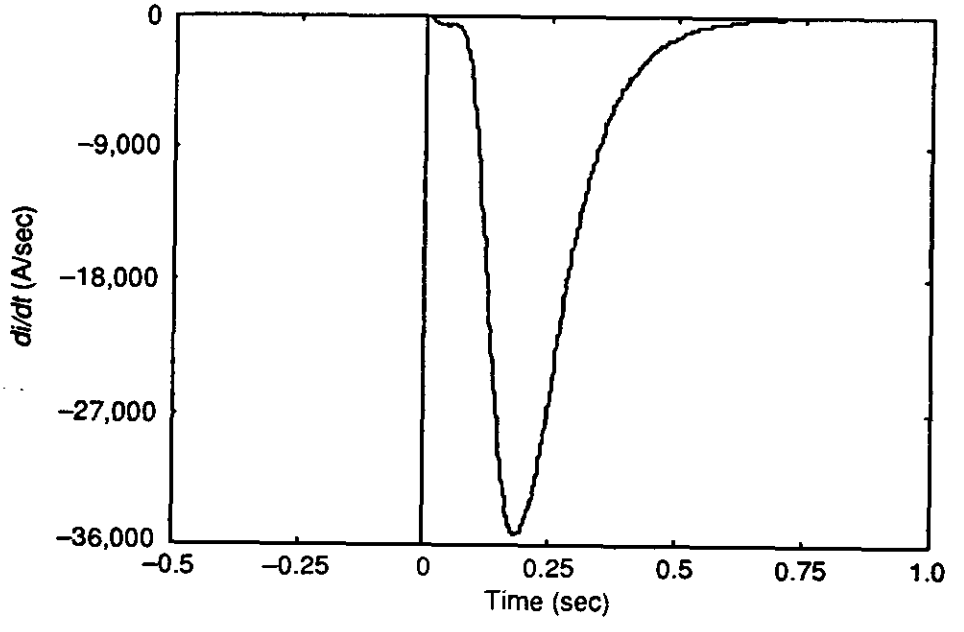

Figure 3(b). The *di/dt* of String Current Decay from the Quench on October 8, 1991. This result is a convolution of the data in Figure 3 (a) with a finite impulse response low pass filter designed using a Kaiser window.[2] Filtering was required for reducing the noise introduced from quantization error.

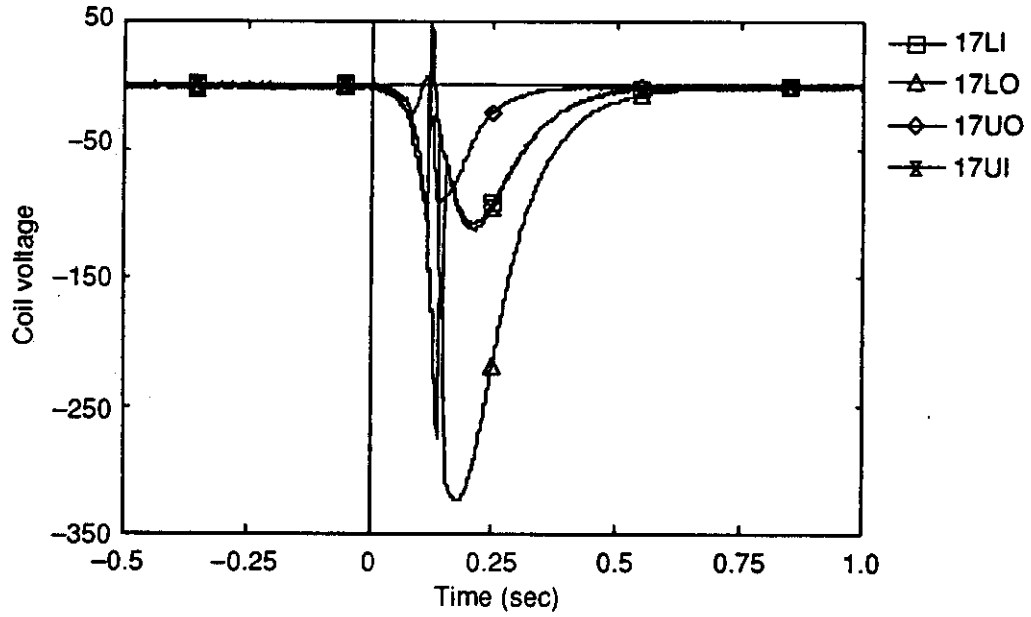

Figure 4(a). Coil Voltage for D-0017. Note that at $t = 0$ all the voltages are going negative, indicating an inductive voltage with little or no resistive component.

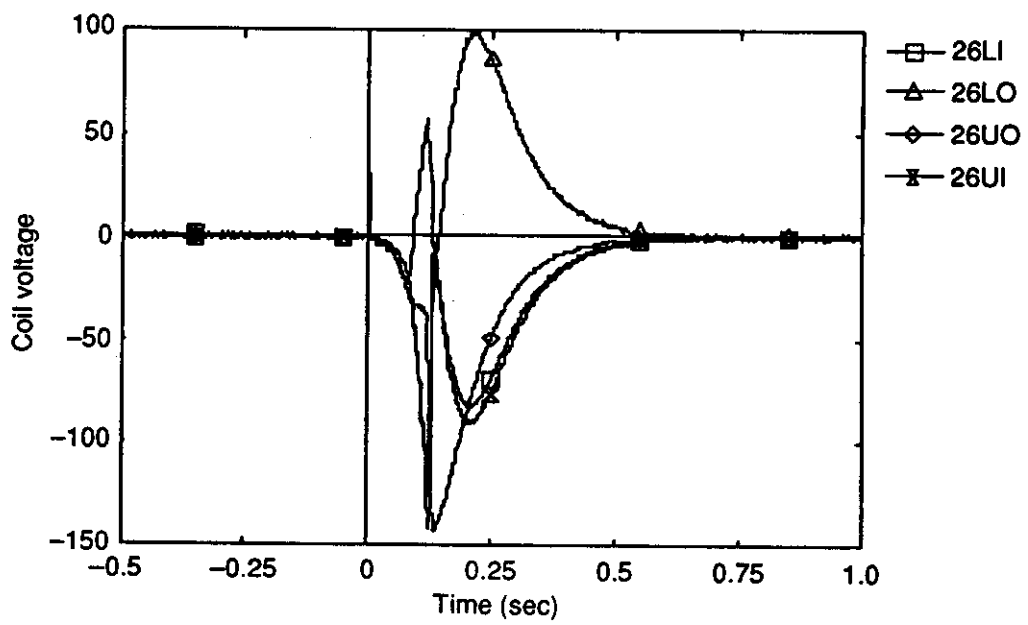

Figure 4(b). Coil Voltage for D-0026.

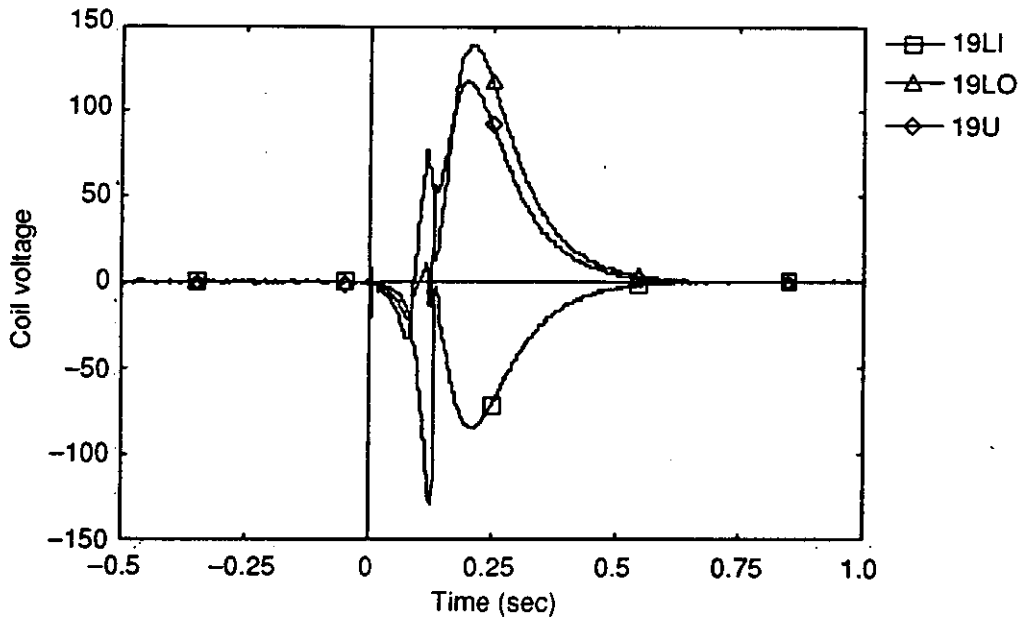

Figure 4(c). Coil Voltage for D-0019. The quarter-coil voltage tap located between the upper-inner and the upper-outer coils failed during cooldown. 19U represents the differential voltage across both upper-quarter coils.

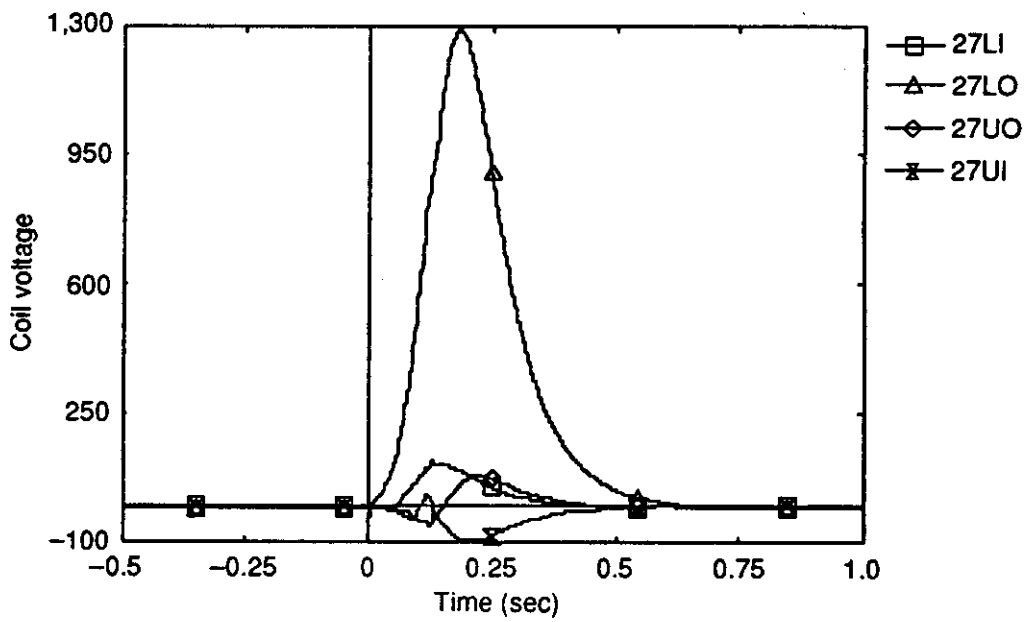

Figure 4(d). Coil Voltage for D-0027. The lower-outer coil experienced a training quench. The large voltage that developed during the quench was unexpected and is attributed to the differences in the strip heaters between dipole magnets.

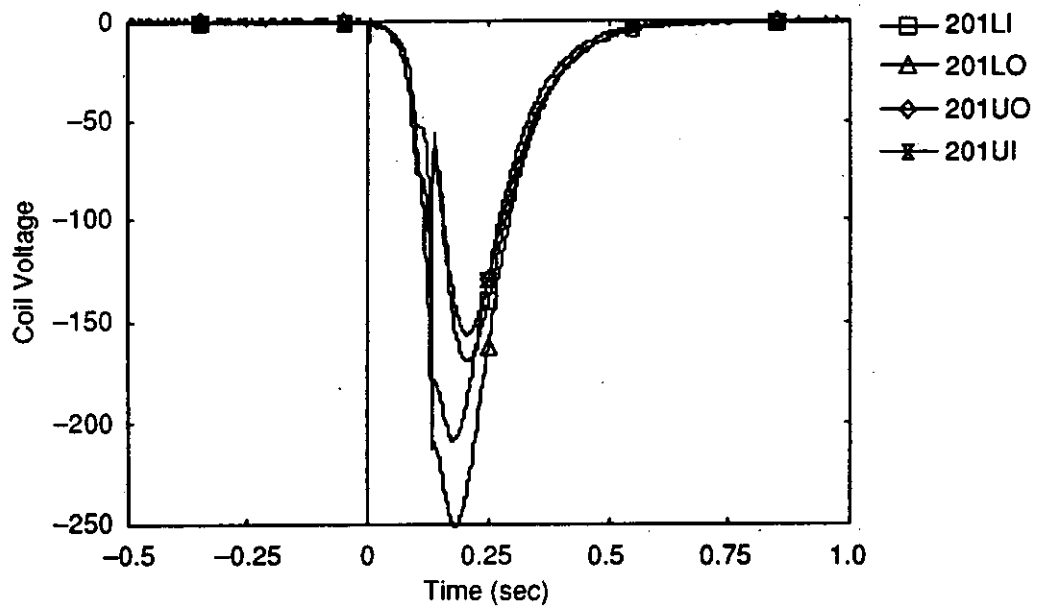

Figure 4(e). Coil Voltage for D-0201. Note that all the voltages that are initially developed are inductive. Much of the stored energy is dissipated in other magnets.

The temperature of the conductor in the region where the quench originated is an important quantity. Damage to the kapton insulation and degradation of the superconductor occur if the temperature rises above a critical value. The maximum temperature of the quenching region is related to the integral over the time of the current squared. This integral, divided by 10^6, is the MIITS integral.[1] The MIITS for this quench event is determined over the interval of current decay beginning when the lower-outer coil of D-0027 started to develop a resistive voltage. Figure 4 (d) illustrates voltages developed in D-0027 during the quench. The MIITS is determined by

$$\text{MIITS} = 10^{-6} \int_{t_o}^{\infty} i^2(t)\, dt = 8.65, \tag{1}$$

where $t_o = -15$ msec.

The coil voltage is a combination of the inductive voltage resulting from change in current in a coil and a resistive voltage resulting from current passing through the copper in the superconductor wire. The coil voltage $V_c(t)$ is given by

$$V_c(t) = V_L(t) + V_R(t). \tag{2}$$

The inductive voltage is determined by the inductance of the coil and the rate of change of current in the coil and is given by

$$V_L(t) = L_c \frac{di}{dt}, \tag{3}$$

with the resistive voltage determined by

$$V_R(t) = i(t)\, R_c(t) = V_c(t) - L_c \frac{di}{dt}. \tag{4}$$

Note that $R_c\,(t)$ indicates that the resistance is a time-varying quantity and is dependent on quench propagation and coil heating. The resistance of the coil is given by

$$R_c(t) = \frac{V_R(t)}{i(t)} = \frac{\left[V_c(t) - L_c \frac{di}{dt}\right]}{i(t)}. \tag{5}$$

Figures 5 (a) through 5 (e) illustrate the coil resistance for each magnet during a spontaneous quench event. The coil resistance is dependent upon the specific superconducting cable used in each magnet and its temperature. Given the cable resistance as a function of temperature and length, it is possible to estimate the integrated temperature across each coil. This information can lead to estimates of stress induced by the differential temperature between coils contained in each magnet.[3]

To serve as a check on the resistance calculations, the current decay of the string is approximated by

$$i(t) = i(t - 0.001)\, e^{\left(\frac{-R(t) * 0.001}{L}\right)}, \tag{6}$$

where $R(t)$ represents the sum of resistances of all the coils, and L is the combined inductance of the string. Figure 6 shows the difference between the current calculated in Eq. (6) and the current $i(t)$ plotted in Figure 3 (a). The residual error is attributed to the additional resistance in the power bus, leads, etc., that contribute to energy dissipation in the system. Errors in the measured coil inductance and changes in inductance due to core saturation also contribute to this error.

Knowing the resistance of each coil, it is possible to determine how the energy is being dissipated in the string. The total energy stored in the string is given by

$$W_L = \frac{1}{2} L\, i_o^2, \tag{7}$$

where L is the string inductance and i_o is the string current before a quench occurs. For i_o = 6600 A (from Figure 3(a)), the energy storage in the string is $W_L \approx 5$ MJ. The energy deposition for each coil is determined by

$$W_{R_c} = \int_{t_o}^{\infty} R_c(t)\, i^2(t)\, dt, \tag{8}$$

where t_o represents the time at which resistance in the coil is detected. Figures 7 (a) through 7 (e) illustrate how energy stored in the string is being dissipated.

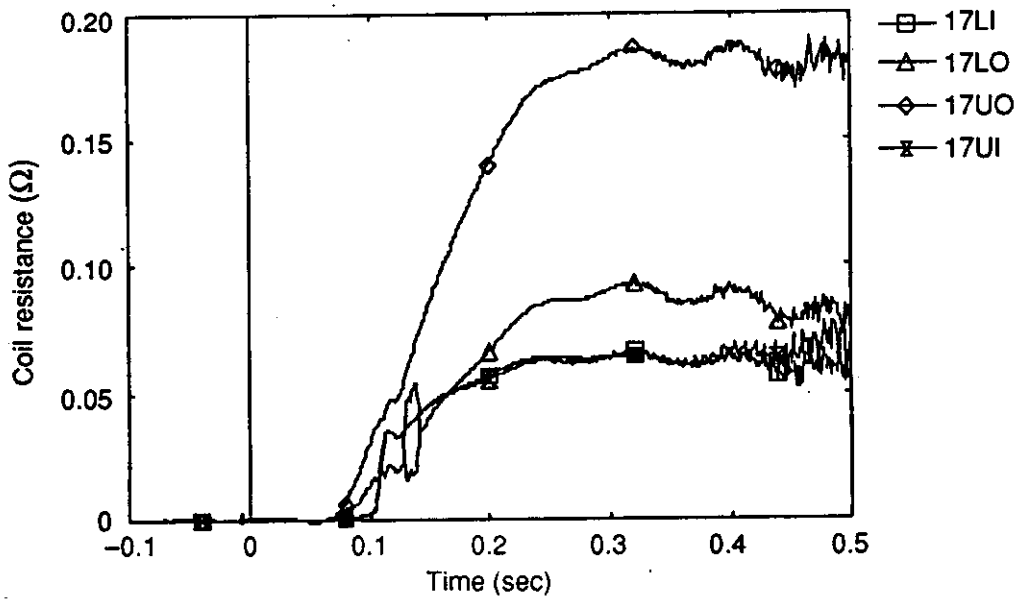

Figure 5(a). Coil Resistance of D-0017 as the Quench Propagates through the Magnet. The difference in the coil resistance between the lower-outer coil and the upper-outer coil is due to a defective strip heater.

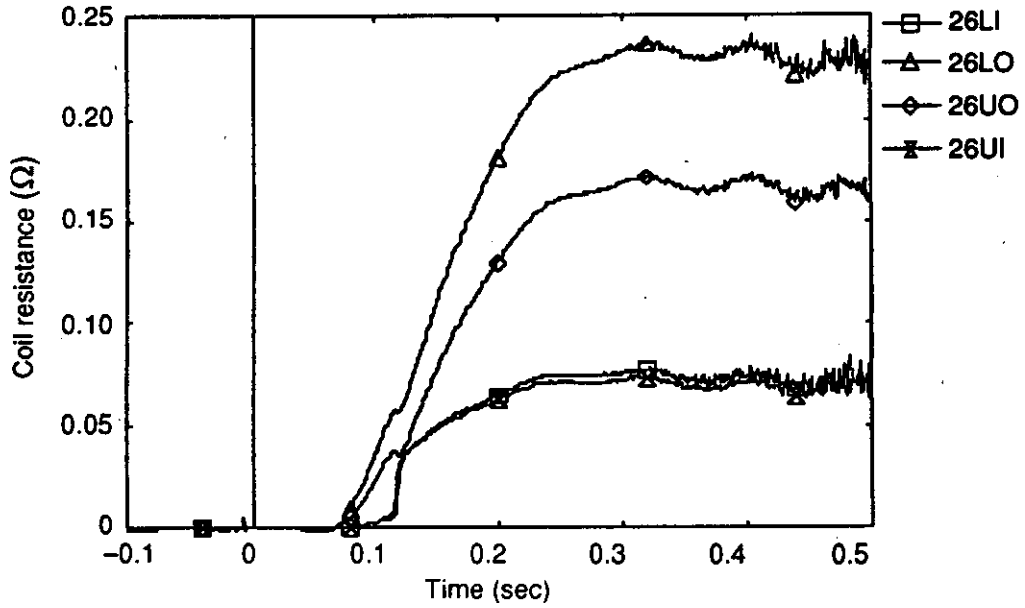

Figure 5(b). Coil Resistance for D-0026.

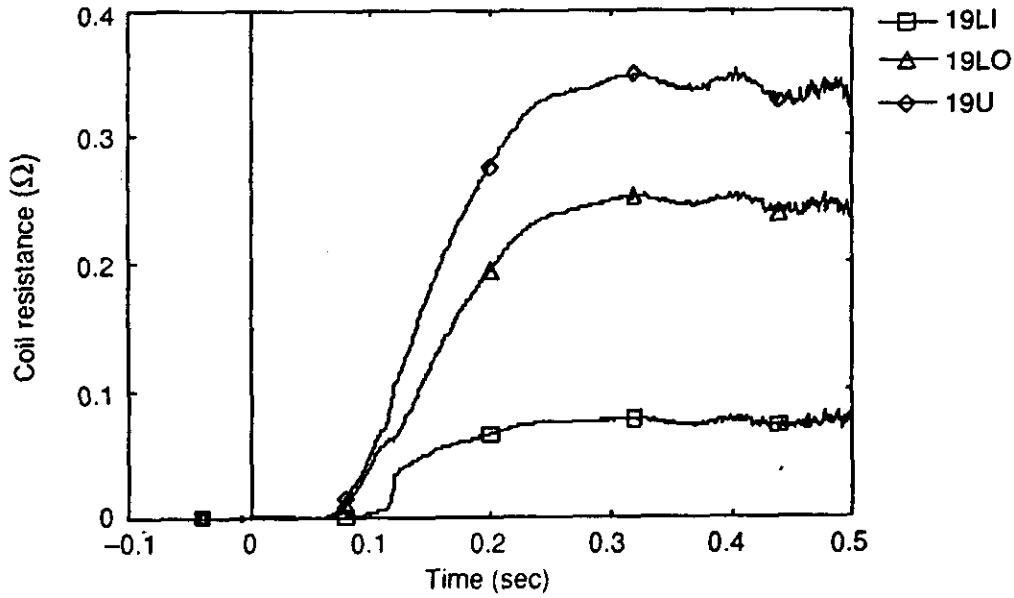

Figure 5(c). Coil Resistance for D-0019.

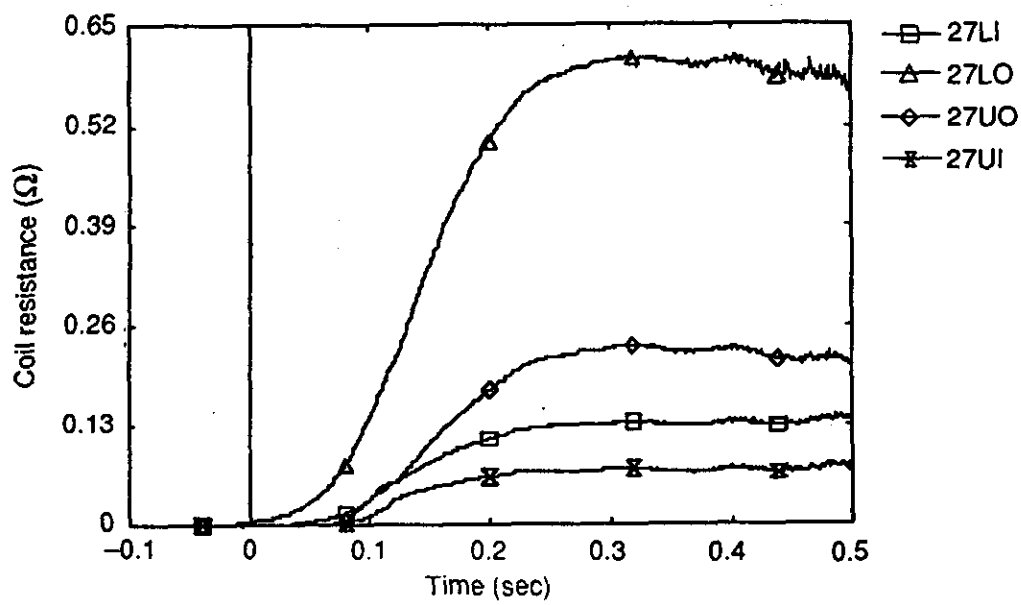

Figure 5(d). Coil Resistances of D-0027 Undergoing a Spontaneous Quench. The higher resistance in the lower-outer coil compared with the upper-outer coil is due to the higher temperature the lower-outer coil experienced during quench.

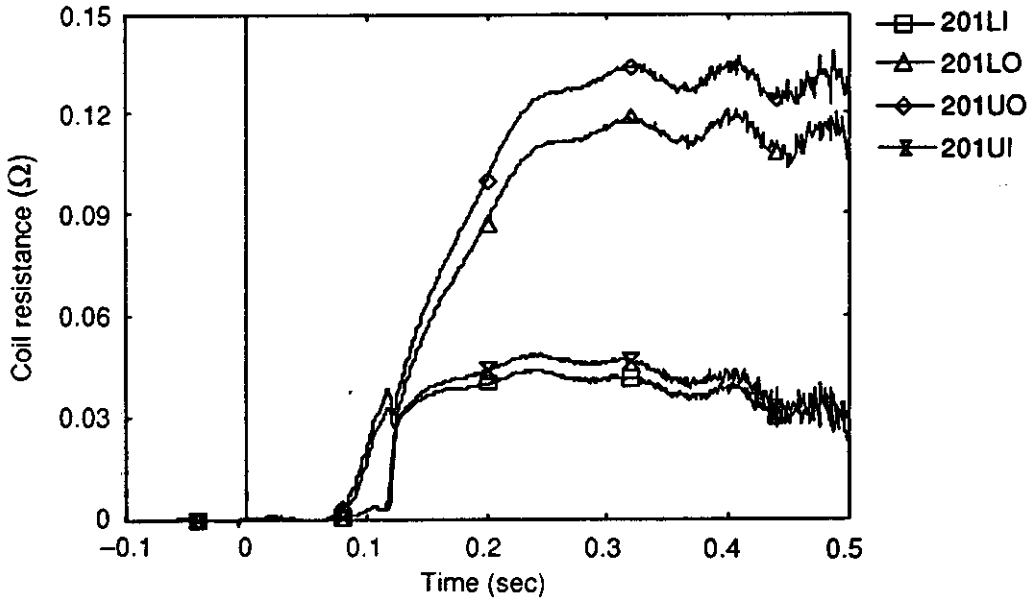

Figure 5(e). Coil Resistances for D-0201.

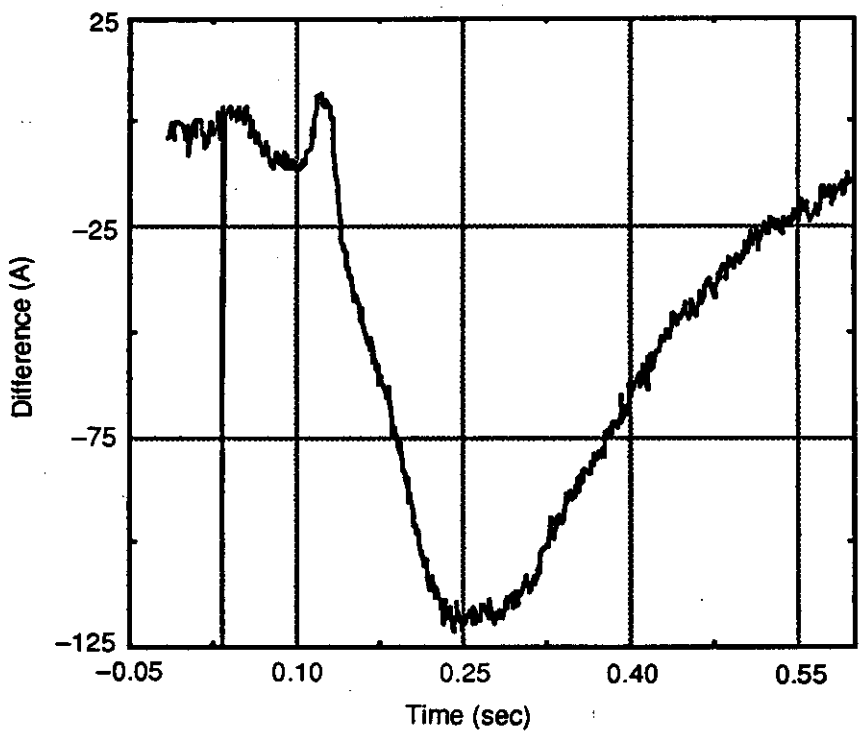

Figure 6. Difference between the String Current Shown in Figure 3 (a) and Eq. (6).

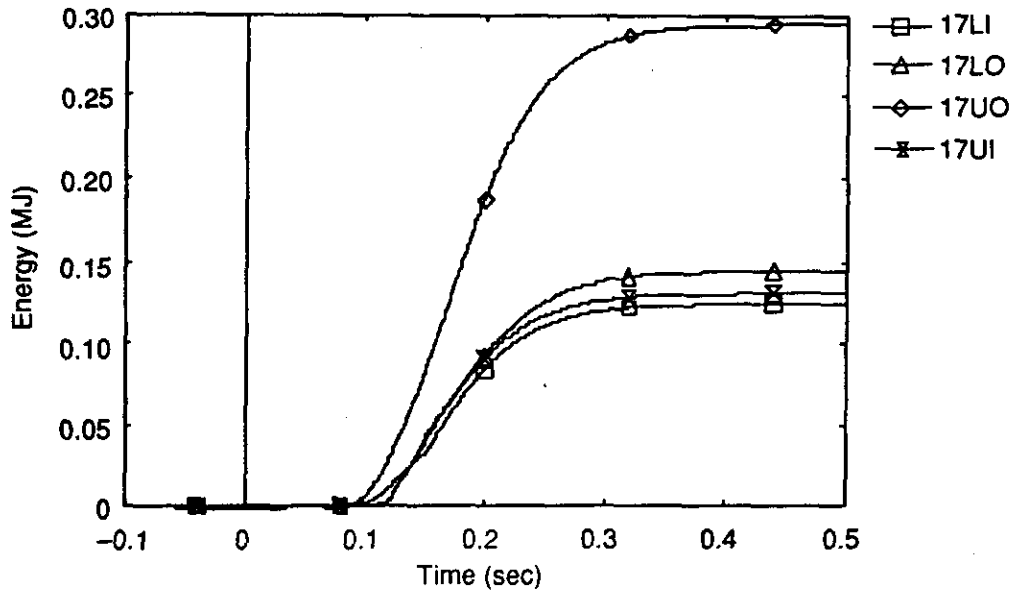

Figure 7(a). Energy Dissipation of D-0017. The lower-outer coil is not quenching as it should when the strip heaters are fired.

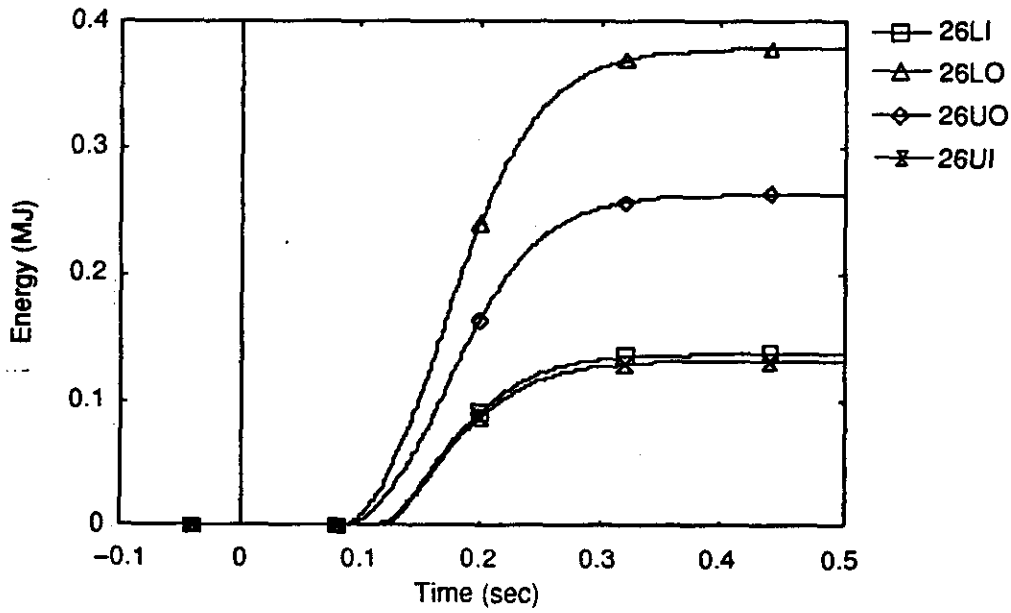

Figure 7(b). Energy Dissipation of D-0026. The upper-outer coil is not quenching as effectively as the lower-outer coil.

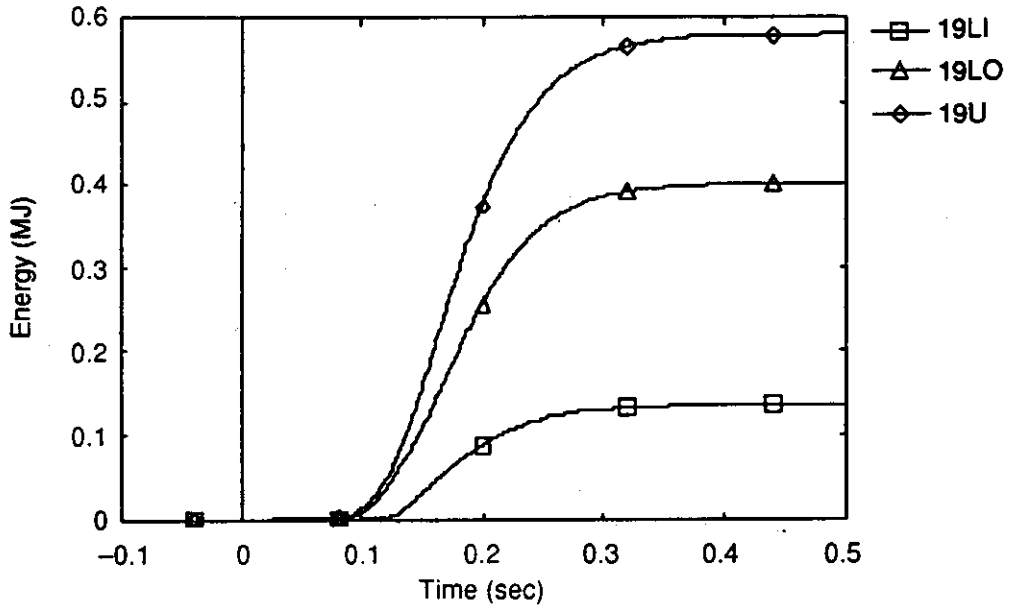

Figure 7(c). Energy Dissipation of D-0019.

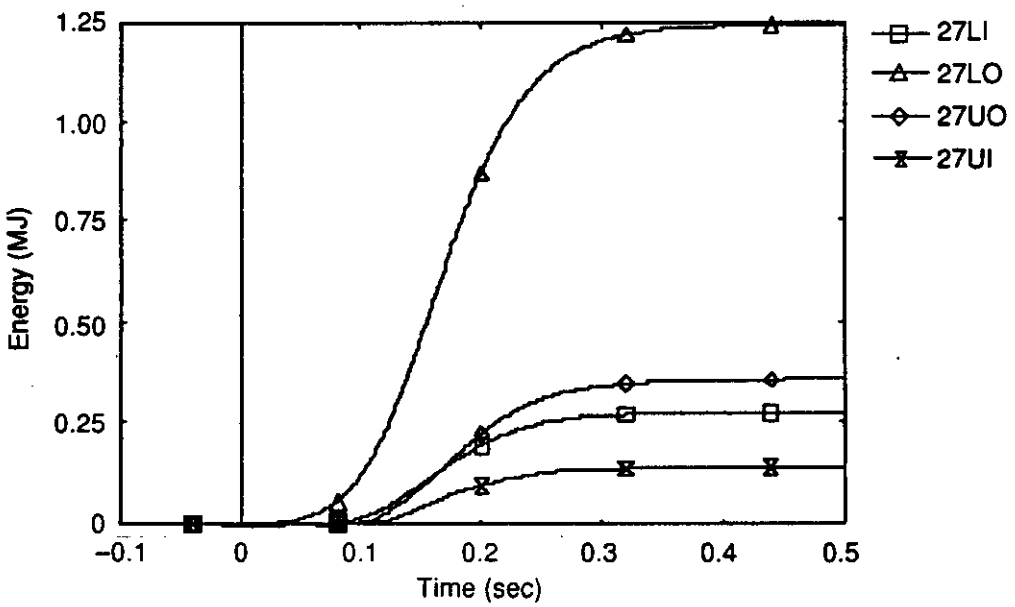

Figure 7(d). Energy Dissipation of D-0027. Note that the lower-outer coil is dissipating 25% more energy than that stored in the entire dipole.

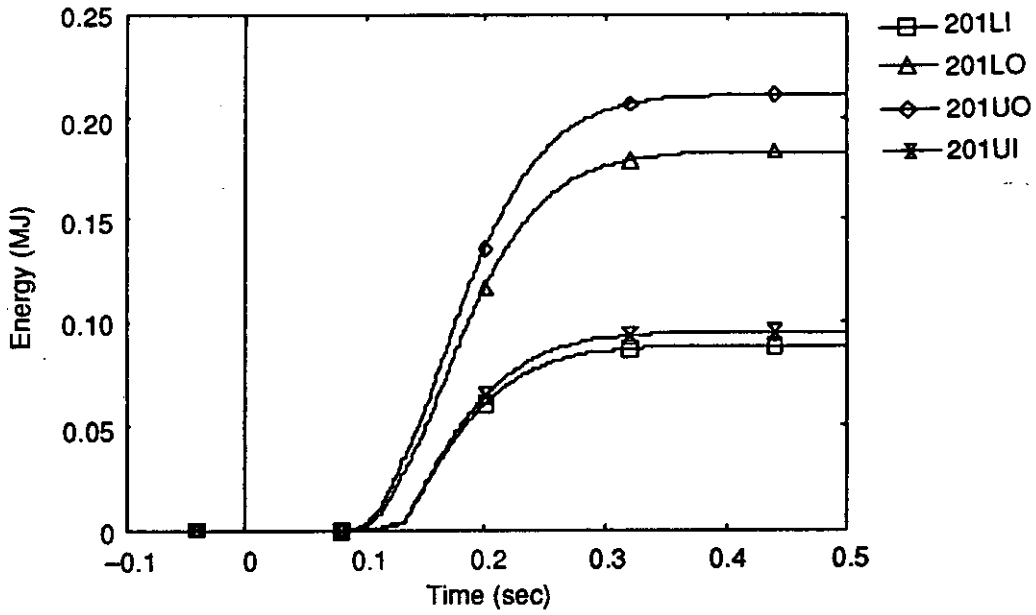

Figure 7(e). Energy Dissipation of D-0201. The lower energies dissipated in the outer coils of D-0201 indicate that the strip heaters are not effective in forcing the magnet to participate significantly in the quench. Compare with the data of D-0026 in Figure 7 (b).

4.0 RESULTS

Fifteen quenches occurring between August 26, 1991, and November 7, 1991, were studied. Four of the quenches were spontaneous; the remainder were induced by firing the strip heaters. All of the magnets exhibited training quenches as the string was brought up to its maximum operating current of 6600 A. (Data on the training quench for D-0019 were lost.) Table 1 summarizes the quench data collected. As can be seen in the spontaneous quench data illustrated in Figure 8, the energy dissipated in the quenching dipole was approximately 2 MJ except for the spontaneous quench of D-0201. Also note that the energy dissipated by D-0201 during the peak 2-MJ quenches is very low. When D-0201 experienced a spontaneous quench, the peak energy deposited in the magnet was a little less than 1.3 MJ. This illustrates how D-0201 acted as a "donor" in driving up the MIITS and peak voltage of the magnets undergoing a spontaneous quench.

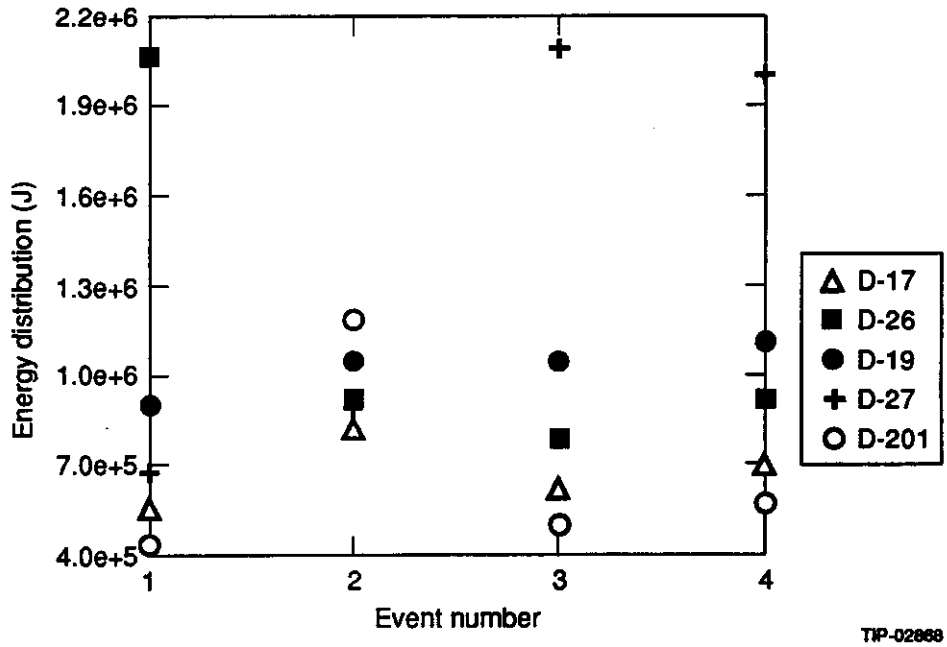

Figure 8. Energy Distribution for Four Spontaneous Quenches from 8/27 to 10/8/91 (see Table 1).

Figure 9 illustrates the strip heater-fired quench events. As noted previously, D-0201 dissipates the least amount of energy of all the magnets because of the ineffectiveness of the strip heaters. D-0019 dissipates the most energy because it operates with the lowest margin of all the magnets.

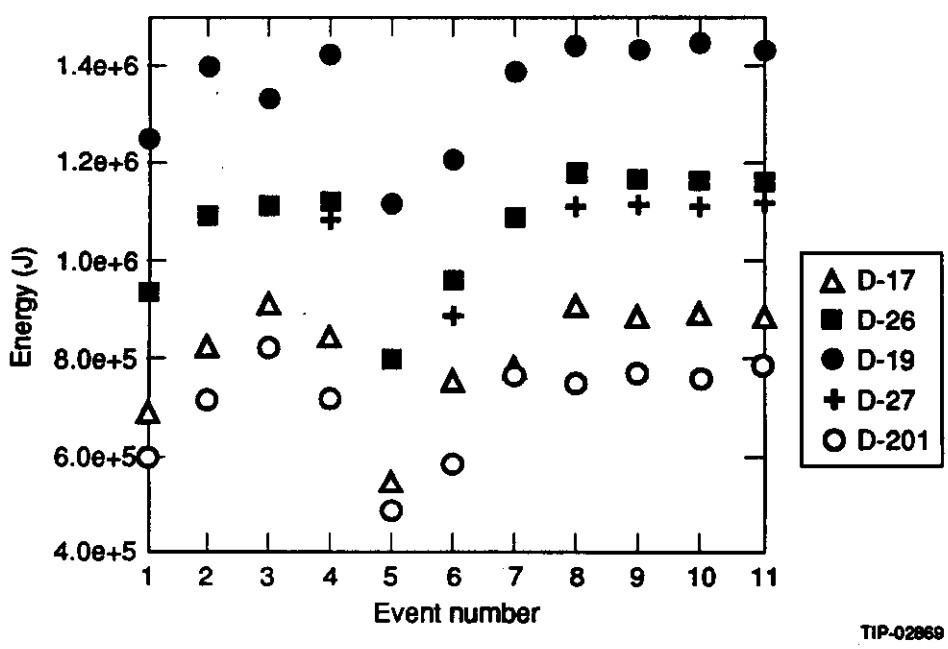

Figure 9. Energy Distribution for Strip Heater-Induced Quenches from 8/26 to 11/7/91 (see Table 1).

TABLE 1. SUMMARY OF THE ELECTRICAL QUENCH DATA COLLECTED FROM THE STRING TEST. There were problems with the power supply that caused Event 7 to occur. The power supply was eventually replaced. The quench start times were measured with respect to the time the heater firing units discharged their energies into the strip heaters. Peak voltage is the highest potential observed with respect to ground.

EVENT NUMBER	DATE (1991)	PEAK CURRENT (A)	QUENCH TYPE/LOCATION	MIITS	QUENCH START (SEC)	PEAK VOLTAGE
1	August 26	5980	Strip heater	5.54	0.077	618
2	August 27	6159	D0026-UO	8.83	–0.025	1070
3	August 29	6302	D0201-LO	9.16	–0.027	362
4	August 30	6379	D0027-LO	9.2	–0.026	957
5	August 30	6434	Strip heater	5.72	0.067	669
6	September 4	6522	Strip heater	5.58	0.066	511
7	September 6	6551	Power supply	5.27	0.068	489
8	October 1	5528	Strip heater	5.45	0.085	449
9	October 1	5961	QDC4 lead trip	5.19	0.077	639
10	October 8	6562	D0027-LO	8.65	–0.015	858
11	October 10	6507	Strip heater	5.49	0.069	548
12	October 15	6601	Strip heater	5.32	0.069	385
13	October 16	6601	Strip heater	5.41	0.069	687
14	October 18	6601	Strip heater	5.37	0.07	705
15	November 7	6601	Strip heater	5.29	0.066	408

5.0 CONCLUSION

The first phase of the string test was composed of only two magnets.[4] Data collected during that phase provided the information needed to properly plan the operations for the five-dipole string. The results from the five-dipole string test provided significant data for the ASST. Several modifications in the design and integration of the ASST string test were influenced by these results. Most importantly, the experience gained at FNAL provides us with the experience we need to configure five dipoles for the ASST with reduced risk. The algorithms presented here enabled us to accurately access the performance of the FNAL string. They also illustrate the problems that can arise when components of the system do not exhibit uniform operation. These algorithms are undergoing further development and will be applied to the data obtained from the ASST.

ACKNOWLEDGEMENTS

These results represent several months of dedicated effort and professional performance of the team that configured and operated the string test at FNAL. We gratefully acknowledge Dick Applegate, William Burgett, Roger Carlone, Jerry Darby, Carl Dicky, Tom Dombeck, Kurt Goetze, John Gran, Mike Hentges, Chris Kelly, Phil Kraushaar, Phil Martin, Jerry Morris, Roger Nehring, Gerry Sorrensen, Jay Theilacker, Gerry Tool, Dave Wallace, John Weisend, and Chuck White for their contributions.

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