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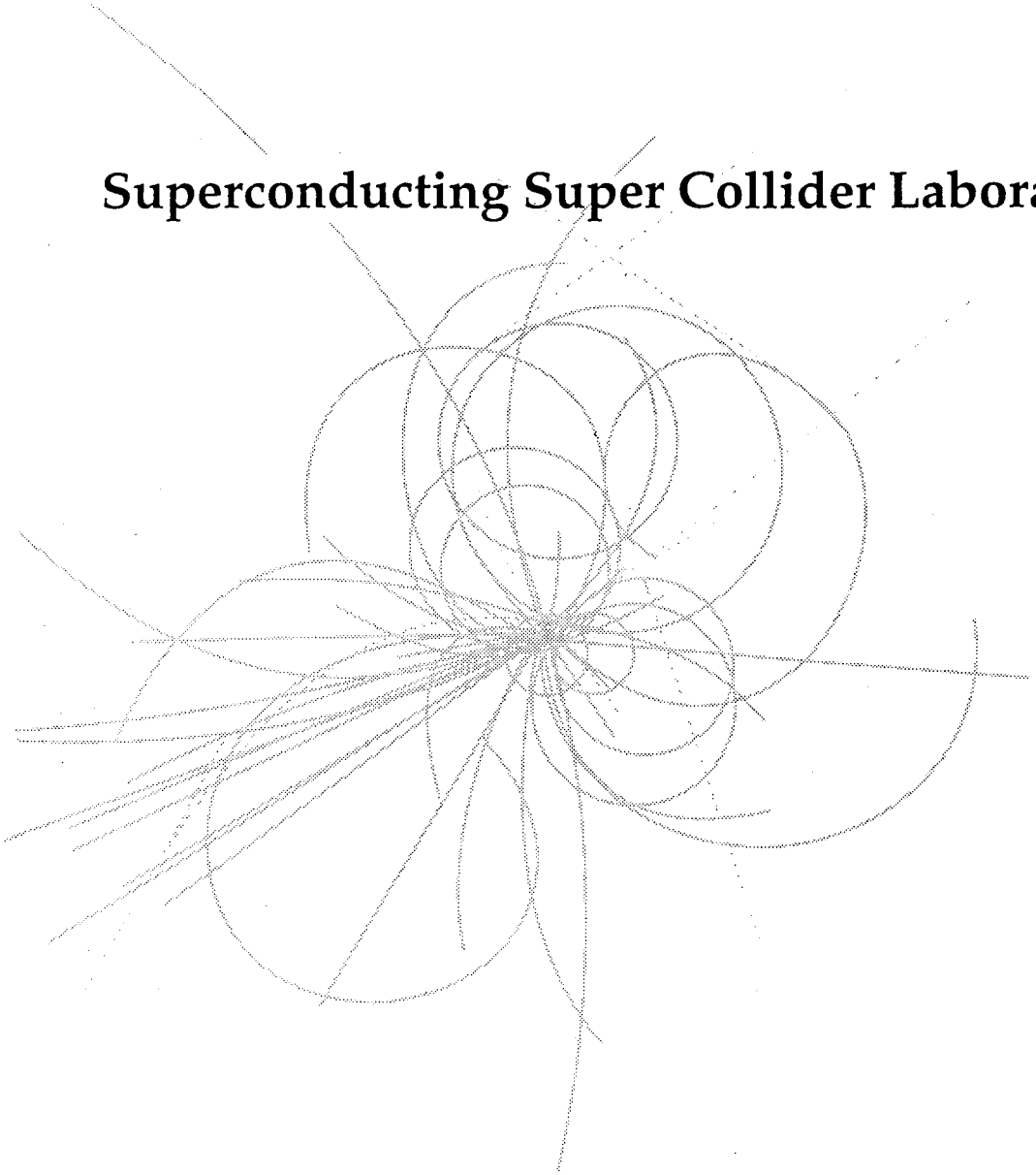

DCA211 Failure Analysis Report

R. Scanlan and C. Arden

June 1992

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R. Scanlan

Lawrence Berkeley Laboratory
Berkeley, CA 94720

C. Arden

Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave.
Dallas, TX 75237

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1.0 INTRODUCTION

This report contains the findings, conclusions, and recommendations of a committee that was commissioned to investigate the events leading to the burnout of the main power connection to the test stand in dipole magnet DCA211 during tests at Brookhaven National Laboratory (BNL) on April 8, 1992. The committee was chaired by R. Scanlan, Lawrence Berkeley Laboratory (LBL), and reported to R. Coombes, Deputy Head, Superconducting Super Collider Laboratory (SSCL) Magnet Systems Division. The committee members were: C. Arden, SSCL; D. Chambers, SSCL; M. Churman, SSCL; W. Clay, SSCL; G. Cottingham, BNL; J. Dryer, SSCL; T. Fagan, Westinghouse; C. Gibson, General Dynamics. The report contains an executive summary of the significant findings, conclusions, and recommendations; this summary is followed by a more detailed compilation of reports, calculations, and data that were used by the committee to reach our conclusions.

2.0 SUMMARY AND CONCLUSIONS

2.1 Primary Cause of Failure

The primary cause of the failure of the main power connection to the test stand (bus) was the omission of the bus voltage tap output from the quench detection/quench protection circuit for DCA211. The lower main power lead quenched in a region between the splice joint and the thermal expansion loop. This quench went undetected for between 6 and 30 sec during which the bus overheated and began to decompose. This decomposition (melting of the metal and burning of the insulation) resulted in lower-to-upper bus and bus-to-ground shorts. This ground current was detected, and the magnet protection circuit was activated. However, by this time, the bus insulation was deteriorating and much of the magnet energy was dissipated at the quench origin. This resulted in the vaporization of the lower bus for a distance of about 15 in. and the upper bus for about 12 in.

2.2 Four Scenarios That May Be Responsible

The committee has identified four scenarios that may be responsible for the bus quenching. Since three other magnets at BNL and five magnets at Fermi National Accelerator Laboratory (FNAL) have been built and tested with this type of bus, we looked for differences between DCA211 and the other magnets.

2.2.1 Scenario 1

The autopsy indicates that the most likely origin of the quench is in a region adjacent to the bus/feed can splice, where the copper braids were not soldered to the superconductor cable during the installation of the magnet on the test stand at BNL. The braid and cable were left unsoldered for a short distance at each end of the bus by the bus manufacturer in order to make the installation easier. The intended installation procedure was to trim the components to obtain a proper fit and then to solder the braids to the cable over the remaining length. However, in the DCA211 installation, the copper braid was not soldered to the superconductor cable for a distance of about 7 in. It is essential that the braids be soldered to the cable in order to provide enhanced stability to the cable. The bus is soldered completely in the magnets at FNAL. We do not know how much bus was left unsoldered in the other magnets at BNL. We conclude that the importance of soldering the braid to the cable over the entire length of the bus was not communicated effectively to the technicians who actually made the joint between the bus and the test stand. Calculations by Cottingham lead the committee to conclude that the bus with an unsoldered length will be very sensitive to small heat inputs to the cable, such as friction between strands at the internal surfaces (knuckles) of the cable. Also, the bus without solder is very flexible and is more likely to move compared to the situation where it is fully soldered.

2.2.2 Scenario 2

The manner in which the braid was soldered to the splice joint, in conjunction with the poor current-transfer path at the unsoldered region, could have resulted in an electric potential difference between the cable and the braid. This could lead to micro-arcing between the cable and braid if the contact changed, for example, due to motion caused by the Lorentz force during ramping.

2.2.3 Scenario 3

There is an indication of heating in the feed can region. Three possibilities were examined: (1) heat from the vapor cooled leads, (2) noise in the thermometry, and (3) temperature rise in the liquid helium (LHe). The first possibility was eliminated by looking at the temperature readings at other thermometers on the vapor-cooled leads. The second possibility is unlikely, since the magnitude of the temperature excursion (+25 mK) is above the maximum noise level specified in the Lake Shore Thermometry Catalog (10 mK). The third possibility is most likely.

2.2.4 Scenario 4

Initial suspicion also was raised concerning eddy current heating, since this was the first high ramp rate (50 A/sec) applied to this magnet. However, nobody has been able to calculate a significant heat input from this source using reasonable values of intra-strand and inter-strand resistances. Also, the stability tests performed at Massachusetts Institute of Technology (MIT) showed no effect up to ramp rates of 200 A/sec.

3.0 RECOMMENDATIONS

The committee presents the following recommendations:

1. In all future tests of SSC magnets, the entire length of the bus should be equipped with voltage taps. These voltage taps should be integrated into the magnet quench detection/magnet protection circuits. Given the critical nature of the quench detection/quench protection process, the use of redundancy in the electronics and protection circuitry should be seriously considered.
2. Project management should require strict adherence to the bus assembly and soldering procedures that have been developed by MIT for this bus. Special attention should be paid to repair/rework procedures, since this bus design is also sensitive to too much solder.
3. We recommend that the present specifications, listed below, be reviewed in the hope that a simpler design might be used. This recommendation is not based on the performance of the bus in DCA211, but on the perceived difficulty of manufacturing and inspecting the present bus design.
   - The bus must tolerate a heat input of 240 mJ/cm without quenching
   - The bus must develop an electrical potential of 0.5 V, which will be used to trigger an active quench protection system.
   - The active quench protection system will remove current from the bus with a decay time constant of 2 sec.
4. While the fabrication of this bus is not implicated in the failure of DCA211, the committee recommends that additional testing should be performed to ensure that the bus will meet the requirements of the SSC. These tests include the following:
   - MIITS limit tests. A quantitative measure of the ability of the bus to absorb energy without damage should be obtained.
   - Fatigue limit tests. The fatigue lifetime of the braid-to-cable solder seam should be measured under the stress and cyclic conditions predicted for the SSC magnets. The

fatigue lifetime for the bus-to-magnet lead splice joints should be measured, again, under the conditions predicted for the SSC magnets.

- Additional effort should be made to identify an effective test for the quality of the solder joints after the cable-to-braid and the bus-to-magnet lead joints are completed.
- Additional stability tests, in which the heat is introduced internally into the superconducting cable instead of externally into the copper braid, should be considered.

5. An alternative joint preparation procedure, which will avoid the possibility of an electric potential between the cable and braid, should be evaluated.

4.0 SUPPORTING DATA AND ANALYSES

4.1 Summary of Items Unique to the Test of DCA211 at BNL

Magnet DCA211 was the first 50-mm-aperture dipole tested on test stand bay B. Prior to testing this magnet, a 40-mm-aperture quadrupole (QCC-403) was successfully tested. After test bay B was repaired from DCA211, it was used to test the Accelerator System String Test (ASST) SPR spool. During the second thermal cycle on the spool, the test stand failed to maintain a vacuum, and spool testing had to be stopped.

Test bay B was having problems maintaining its vacuum due to leakage around the indium seals. The vacuum was maintained with the addition of a turbo-molecular pump. The vacuum problem results in increased time required to recover from a quench, from approximately 1 h to 5 h. The power lead in DCA211 that quenched is located within the single-phase helium at 4 atm. However, it is feasible that if the vacuum degraded around the upper bus end tube, and heat was transmitted across the vacuum space to the bus in the area of the power lead, this could cause the bus to quench. The vacuum data from BNL shows a reading of 1*10 E-5 Torr at 7:15 a.m. the day of the event. No further readings of the vacuum were recorded before the quench occurred at approximately 8:45 a.m.

Magnet DCA211 was the first Brookhaven-built counterclockwise magnet. The bus configuration showed no effect on the anomaly, as the event occurred at the opposite end of the magnet and the disassembly of the coil splice to the bus showed the superconductor to be unchanged from the time it was assembled.

— C. Arden

4.2 Possible Heating in the Feed Can Prior to the Quench

There was some indication of heating in the feed can region. Four possibilities were examined:

1. heat from the vapor-cooled leads,
2. noise in the thermometry,
3. convection currents in the helium bath, and
4. heating from the normal conductor.

The following is a description of the system, some of the pressure and temperature readings recorded on the data-acquisition system, and the results of analysis performed by BNL personnel. (Copies of the pressure and temperature data are found in Appendix A.)

The slow data logger recorded readouts from two temperature sensors located in the main lead pot (a 23-l volume in the power feed can) and from warm pressure transducers attached to the lead and end cans. On April 8 from the start of the data at 08:45:23 to 08:47:04 (elapsed time of 1:41), the two Lake Shore temperature sensors (T.S.) gave the following reading:

T.S. #7 4.0135 K $\pm$ –0.0025 K

T.S. #8 4.5933 K $\pm$ –0.003 K.

In the next 18 seconds, T.S. #7 rose to a value of 4.048 K, a delta of 0.035 K or more than 10 times the previous deltas. T.S. #8 rose to a value of 4.620 K, a delta of 0.027 K or just less than 10 times the previous deltas.

These same sensors, while being used with DCA207, November 11, 1991, showed a temperature decrease of 30 mK over a time period of 2 min. The temperature decrease was explained by Joe Muratore of BNL as being caused by the opening of valves on the vapor-cooled leads, resulting in an increase in coolant flow.

Pressure data recorded for this same 18-sec interval also showed successively increasing readings; however, the active pressure regulation of the system makes it hard to draw any conclusions from this fact.

The volume of LHe in the feed can was estimated at 40 l by Al Prodel of BNL. This is the result of adding the two 23-l volumes in the feed can plus the piping associated with the feed can snout, then subtracting for the volume of the wiring in those volumes. The total volume of LHe in the magnet, feed can, and end can is 300 l.

The LHe flow travels from the magnet into the feed can via the upper and lower single-phase lines on the magnet at a mass flow rate of 160 g/sec. Margarita Rehak of BNL calculated the flow in the upper single-phase line where the bus and leads connect as 60 g/sec. The 60-g/sec flow in the upper line mixes with the 100-g/sec flow in the lower line at a plenum located at the attachment point formerly used for the 40-mm magnets, and then divides into two flow streams with one stream going to the lead pot with the main power leads and the other going to the instrumentation lead pot. The flow distribution between these two streams is not equally divided. At this time, how the flow divides after leaving the plenum is unknown; however, it is believed the main lead pot receives the majority of the flow.

4.2.1 Possible Implications

This section includes an interpretation of the foregoing data along with calculations based on that data.

1. Heat did not flow down the leads to the solder joint. The temperature increase of the leads is much too low to have affected the superconducting ability of the SSCL cable, and it occurred almost 3 m upstream in a high LHe-flow condition. Thus, it is not possible for heating from the leads to have caused the quench in the conductor.

2. The tenfold increase in the delta temperature recorded by the thermometers above what they had previously recorded on both DCA211 and DCA207 indicate that they were seeing some event. The fact that these thermometers could have been on the same current and/or voltage supply cannot be ignored. Even so, that gives grounds only for a common mode failure of the two sensors, and BNL has not reported such a failure. As for the temperature rise being due to thermal currents as seen in the ocean, the thermal diffusivity of water and LHe are within a factor of three of one another. However, thermal currents in the ocean require some heat source, usually solar or geothermal, to generate them. The test stand at BNL is thought to be well-insulated; after passing through the extension tube on the magnet and the plenum on the test stand it would be hard to prove that the flow was anything but well-mixed forced flow.

3. The temperature and possible pressure increases could have been the result of heat added to the system by a normal section of conductor. If this heat were added to the system by resistive heating of the leads, the time period from the conductor going normal to the conductor melting would be the sum of the time shown on the temperature plots as a temperature rise and the time of flight of the LHe from the normal zone to the sensor (and a possible additional 7 sec of unrecorded time due to the failure of the slow data logger to take data once the fast data logger begins). Thus, the time of conductor heating is 18 sec plus the time for warmed LHe to get to the sensor almost 3 m away, plus another possible 7 sec.

The lack of data concerning the distribution of flow between the two lead pots prevents an accurate calculation of the time of flight; but, a lower limit can be placed on it if we assume that all the flow goes into the lead pot and the available volume for fluid is 15 l. The time of flight then becomes 13 sec, and the time from quench to burnout becomes 31–38 sec. (Of course, all the flow does not go only through the lead pot.)

It has been suggested that the heating of the conductor was adiabatic. As pointed out in a memo from Dick Thome of MIT, the assumption that the melting of the conductor was adiabatic is incorrect, and it leads to an underestimation of the time to burnout for the bus. The adiabatic calculation estimates a burnout time of 6 sec, which is too long for hot metal to be immersed in 4.3-K fluid without significant heat transfer occurring. Additionally, the adiabatic calculation does not account for the energy absorbed by the heat of fusion of both the conductor and the insulation.

The configuration of the unsoldered cable and braid (at the flow outlet of the magnet and soldered to the copper bus bars of the test stand) was almost an optimization of a method to localize a quench in the connection to the test stand. The flow of 4.3-K LHe from the magnet drops the temperature of the bus at the entrance to the magnet, while the copper at the entrance to the test stand acts as a heat sink for the cable/braid assembly.

To build a computer model that would adequately depict the events leading to conductor burnout would require both a great deal of time and many assumptions about the physical make-up of the leads at the time of burnout. However, some basic items are shown in Table 1. The forced convective heat transfer coefficient is calculated for the flow in two locations, the exit of the upper single-phase line and the connection tube where the cable/braid were in a 120-mm-diameter tube with the connector used to connect the magnet instrumentation. The power input to the LHe system required to raise the temperature of the system the amount indicated by T.S. #7 and T.S. #8 is also calculated. The Grashof and Reynolds numbers for the two locations are calculated and compared to show that free convection in the area where conductor burnout occurred plays an important part in the heat transfer between the fluid and the surface. It is important to note that the Grashof number will increase an additional two orders of magnitude before the copper reaches melting temperature.

Thus, it is shown that significant heat transfer could have occurred at lower current levels and that burnout did not occur until ohmic heating surpassed both the conductive and convective heat transfer in the connection.

4.2.2 Recommendation

A knowledge of the time to burnout for a bus conductor at relatively low current (less than 3000 A) is important to properly determine the required detection voltages and burnout times. It is recommended that a suitable organization (possibly MIT) be tasked with determining experimentally the time to burnout for the bus assembly as currently designed at various operating currents.

— H.W. Clay

TABLE 1. QUENCH ON DCA211 BUS LEAD.

QUANTITY	VALUE	UNITS	QUANTITY	VALUE	UNITS
Calculation of heat transfer coeff. for region of splice and unsoldered cable at end of magnet in 120-mm-diameter tube.			Calculation of heat transfer coeff. for region at end of magnet in 57-mm-diameter tube.		
K of He at 4.3 K and 70 psi	2.12E-04	W/(cm-k)	K of He at 4.3 K and 70 psi	2.12E-04	W/(cm-k)
Viscosity of He	4.05E-05	g/(sec-cm)	Viscosity of He	4.05E-05	g/(sec-cm)
Area available for flow	30.81	cm^2	Area available for flow	16.02	cm^2
ρ	0.1389	gm/cc	ρ	0.1389	gm/cc
hydraulic diameter	1.82	cm	hydraulic diameter	1.87	cm
mass flow rate	60	gm/sec	mass flow rate	60	gm/sec
flow velocity	14.02	cm/sec	flow velocity	26.96	cm/sec
Re	8.73E+04		Re	1.73E+05	
Pr	0.709		Pr	0.709	
heat transfer coeff. = hc	2.10E-02	$W/(cm^2\text{-}K)$	heat transfer coef. = hc	3.52E-02	$W/(cm^2\text{-}K)$
Note: These heat transfer coeff. are for forced convection and are calculated from the Dittus-Boelter equation					
Calculation of heating required to raise temp of He in feed can					
Q=m (dot)* ΔT*Cp					
m (dot)	160	g/sec			
Cp He at 4.3 K and 70 psi	3.837	J/(g-K)			
ΔT from TS7&TS8	0.031	K (35+27)/2			
Q	19.03152	W			
Calculation of time to change out cold helium in feed can					
Volume of He in feed can	15	l			
TF (time of flight)	13.021875	sec			
Calculation of the length of normal zone required to produce heating					
Resistivity of Cu at 27 K	2.00E-08	Ω-cm			
Cross section of Cu	0.2622	cm^2			
Current in conductor 31 sec before burn out					
	4500	A			

TABLE 1. QUENCH ON DCA211 BUS LEAD (CONT.).

QUANTITY	VALUE	UNITS	QUANTITY	VALUE	UNITS
AVERAGE Resistance of conductor from $R=P/I^2$					
	9.40E-07	Ω			
MINIMUM length of normal zone (L)					
	12.32	cm			
Voltage across normal zone					
	4.23E-03	V (V=IR)			
Calculation of ΔT required to dissipate heat with hc=0.021			Calculation of ΔT required to dissipate heat with hc= 0.0352		
Area of cable = L* (w+h)*2			Area of cable = L* (w+h)*2		
L = length of normal zone			L = length of normal zone		
width	1.2	cm	width	1.2	cm
height	0.4	cm	height	0.4	cm
area	39.43	cm^2	area	39.43	cm^2
dT = Q/(hc*Area)	23.02	K	dT = Q/(hc*Area)	13.72	K
Note: If the Normal zone is longer – the average Δ temperature will be lower.					
Calculation of Grashof number					
$Gr=g*\beta*dt*D^3/vis^2$					
β	0.0912	1/K	β	0.0912	1/K
Gr	1.45105E+11		Gr	9.3951E+10	
From Kreith – If Gr/Re^2 is greater than one then the effects of free convection cannot be ignored compared to forced convection.					
Gr/Re^2	19.02795284		Gr/Re^2	3.1512814	

4.3 Performance Specifications and Their Impact on the Bus Design

The MIT bus design was driven by three input specifications which, as we understand them, are listed below:

1. The bus must tolerate a heat impulse of 240 mJ/cm without quenching.
2. The bus must develop an electrical potential of 0.5 V, which will be used to trigger an active quench-protection system.
3. The active quench-protection system will remove current from the bus with a decay constant of 2 sec.

These specifications have driven the design effort in an unusual direction, resulting in a novel design. Instead of a bus designed to minimize damage from quench events (maximize MIITS), as is usually the case, this design was driven to minimize the chances of quenching (maximizing its ability to withstand heat impulses without quenching) while satisfying the decay time specified.

In order to satisfy the MIITS rating of a superconductor, copper is usually added. To maximize its ability to withstand heat impulses, the MIT team used the novel concept of introducing and thermally coupling helium into the bus matrix, taking advantage of the very high heat capacity of this material at low temperature. The helium is contained in the voids of a copper braid that is soldered to the superconductor. The copper in the braid serves to thermally couple the helium to the bus matrix. If a heat pulse enters the bus matrix from the outside, it will encounter the helium-filled braid first and, it is hoped, will be absorbed by the helium before it can trigger a quench in the superconductor. This is the quench-triggering mode used to test and evaluate the MIT bus design.

On the other hand, if a heat pulse originates inside the superconductor, which is often the case, the heat must flow out of the superconductor through the solder layer and into the helium-filled braid. This latter process imposes two competing requirements on the soldered seam:

1. Solder must provide adequate thermal coupling between the superconductor and the helium filled braid.
2. Solder must not wick into the copper braid and fill the space reserved for the helium.

These competing requirements create fabrication concerns. Problems associated with factory- and field-soldering of this braid/cable interface and its testing Quality Assurance (QA) will be discussed in another section of this report. These fabrication concerns must now be weighed against other risks, which, it is hoped, are eliminated by the performance specifications.

These concerns about the practicality of the present design suggest that the specifications underlining this design should be reexamined and that alternate designs should be considered.

The important question is: Can the specification for the minimum heat pulse that produces a quench be lowered?

We understand that new worst-case scenarios generate only 70 mJ/cm of heat. If the minimum quench-triggering energy level can be reduced to about 50 mJ (total spread over the minimum propagating zone), the door to practical copper-backed bus designs opens. Any design that incorporates additional copper will provide higher MIITS ratings and, therefore, will permit the bus to rise in temperature and to develop specified signal voltages (0.5 V or more), while retaining more than enough burnout margin to allow current removal in the specified time (2.0 sec or longer).

Copper-backed buses are time-tested. They have been in use for many years (7 years at BNL) without any known quenches. This type of bus is also used in some regions of the HERA magnets with satisfactory results While these buses also involve a soldering process, there are no competing requirements between achieving a good bond and maintaining the void space in the braid, as in the case of the MIT bus. The necessary condition is that the copper and the superconductor be in thermal and electrical contact. Therefore, the soldered seam can be flooded with adequate solder and inspected for a meniscus in a time-tested QA manner.

— G. Cottingham

4.4 Quality Assurance of Solder Joint

The heat input that caused the bus to go normal very likely originated in the region where the superconducting cable and the copper braid were not soldered when the bus was connected to the power leads during installation on the test stand. As discussed earlier, an unsoldered bus has much lower stability than a soldered one. It is, therefore, essential that an inspection method be developed to ensure continuity of the solder joint.

The SSCL has fabricated samples of braids soldered to a cable that included various lengths of unsoldered regions. From these samples it was concluded that large unsoldered areas could be found by visual inspection. However, the possibility exists that smaller areas (less than 5 cm long) will not be discovered by visual inspection alone.

The committee recommends that a quality assurance procedure be developed to detect small unsoldered regions. It was noted from the samples that a unsoldered region caused the stiffness of the bus to noticeably decrease. One possible test for bus stiffness would use a tool with three wheels through which the soldered bus could be pulled. The load on the middle wheel would be monitored. Any change in stiffness would cause a reduction in load on the middle wheel.

The committee also recommends that quality assurance procedures be developed for other soldered joints. These joints include the bus-to-magnet lead joints, the bus-to-power supply lead joints, and the bus-to-bus joints. These joints are of special concern because they are performed by hand, often in cramped field conditions.

— C. Gibson

4.5 Solder Joint Fatigue Analysis Recommendation

Based on personal experience with solder joints, the susceptibility of the bus solder joints to fatigue cracking was questioned by several committee members. The SSC magnets will experience a fatigue environment. This is addressed in the Collider Dipole Magnet (CDM) System Specification, which states that the magnets must be designed to withstand 10,000 magnetic cycles, 150 quench cycles, and 30 thermal cycles.

In the collider magnets, the copper braid/superconducting cable ride in a composite channel extending through both the magnets and the associated interconnect regions. The composite materials are joined in the interconnect region using formed composite pieces together with cloth and epoxy joints to ensure continuation of the composite channels surrounding the cable/braid assemblies. The expansion and contraction of the bus assembly is accommodated by the use of a 250-mm-diameter composite expansion loop inside the cold mass of the magnets. The composite pieces of the expansion joint were fatigue-tested by MIT and found to be acceptable for use in the collider. Finite Element Model (FEM) analysis of copper bars formed into expansion loops of the size currently used indicate that solid bars would not have fatigue problems.[1] It seems reasonable to assert that if solid copper bars did not see stress levels high enough to cause fatigue, then copper braid and cable with a smaller moment of inertia will not have fatigue problems associated with the flexing of the expansion loop. Thus, there are only two areas that may require further analysis for fatigue. The first is the joint between the braid and the cable, and the second is the splice joints between the superconducting cables.

The forces exerted on the joint between the braid and cable can come from only two sources: the axial force resulting from thermal contraction and the transverse force resulting from magnet field effects on a current-carrying conductor. The axial strain in the cable braid joint will be small because the expansion loop accounts for the majority of the thermal contraction of the magnets and spool pieces. There will be a differential thermal contraction between the composite channel and the copper in the cable, which will result in strain in the cable braid assembly. In addition, during each magnetic and quench cycle the bus will undergo cyclic transverse loading due to the interaction of the current in the bus and the resulting self-field and the magnet dipole field. The effect of thermal contraction and transverse loading on the fatigue life of the solder joints needs to be investigated.

The splice joint between the superconducting buses of connected magnets will see some stress due to the difference in the thermal expansion coefficients of the composite channel and the cable/braid assembly. The exact amount of strain produced by this effect and the resulting fatigue life needs to be investigated.

MIT has the most experience in the design of the bus assembly and its manufacture. Thus it is recommended that MIT be tasked to analyze the amount of strain in the solder joints and to predict the fatigue life of the solder joints.

— H.W. Clay

4.6 Fermi Test Stand Review

FNAL includes the power bus in the quench protection system, which has a threshold of 250 mV for the magnet and only 10 mV for the bus. The way FNAL achieves this low sensitivity level without ramp rate sensitivity faults is that the *di/dt* is measured across the magnet and subtracted out. If correction for the ramp rate were not performed, then the bus threshold might be too high to detect a bus quench prior to bus damage. This correction also permits very low bus quench threshold detection and minimizes the false detections.

The FNAL test stand uses three superconducting leads to attach to the power bus leads. These three superconducting leads are 50-mm design cable with a loop and then a splice to a 40-mm design cable, which then attaches to the copper vapor-cooled lead. However, the possibility for an electrical potential exists, as it does in the BNL power lead's solder joint.

FNAL has released the Engineering Specification for making the power lead connection to the test stand. It is specific on the soldering of the leads and includes the copper braid. FNAL does not have as long a lead length as BNL.

The cryogenic flow paths and rates are different for FNAL's test stand.

— *C. Arden*

4.7 Hardware Disposition

After the incident on the test stand (Figure 1), electrical checks were performed to help determine the extent of the damage. It was learned that the coils were intact and that the power bus had an electrical open through the test stand to the magnet. The magnet was warmed up, and the interconnect vacuum sleeves were pulled back. (The vacuum was lost during the incident due to the release of helium into the vacuum vessel.) Pictures of the power bus-to-test stand interconnect were taken to best document the damage. It was obvious that approximately 10–12 in. of the lower-power bus lead on the magnet side of the splice was completely burned away.

The following damage was also noted: the G-10 shell around the power bus lead was burned, and an instrumentation connection had one-third of its copper leads cleanly cut at the interface of the connector halves.

During the initial meeting at BNL, the return end dome (without the extension tube) was cut off utilizing the Wachs cutter (Figure 2). When the end dome had been removed, the bus loop and all the ASST instrumentation boards were found covered in a carbon soot. Again, pictures of the damage were taken to document the area prior to any additional disturbances. It was evident that the G-10 extension clamshell and MIT Bus Pultrusion were burned as well as charred (Figure 3). A bus-to-ground resistance check was measured at 200 kΩ (very low). The upper bus was then separated outside the lead end. The through part of the bus then measured 2 MΩ to ground, while the lower bus and coils remained at 200 kΩ. (20 MΩ is the lowest value required prior to performing a magnet Hi-Pot.)

During the second meeting at BNL, the lead end's dome was removed in the same manner as the return end, utilizing the Wachs cutter. The magnet coils' splice to the power bus was opened and inspected prior to unsoldering the leads. The splice was found to be in the same condition as it was when initially assembled. Once the coils' splice was separated from the power bus, the coils' resistance was checked and the coils were Hi-Potted. The coils' current leakage at 5 kV was an acceptable 50 μA. The decision was then made to remove the bus in DCA211 and to replace it with the one extra bus presently at BNL. The power bus configuration of the magnet was changed from counterclockwise to clockwise. The damaged bus removed from DCA211 will be saved for further analysis. The present plan is to rebuild DCA211 and to cold-test the magnet. This will provide a data point on how a carbon-contaminated magnet can operate in the collider if repaired. It will also provide a lesson learned regarding the possibility of rebuilding a magnet to an operational level. However, it would be more difficult to remove the bus from a production CDM, because the expansion loop is located inside the end plate.

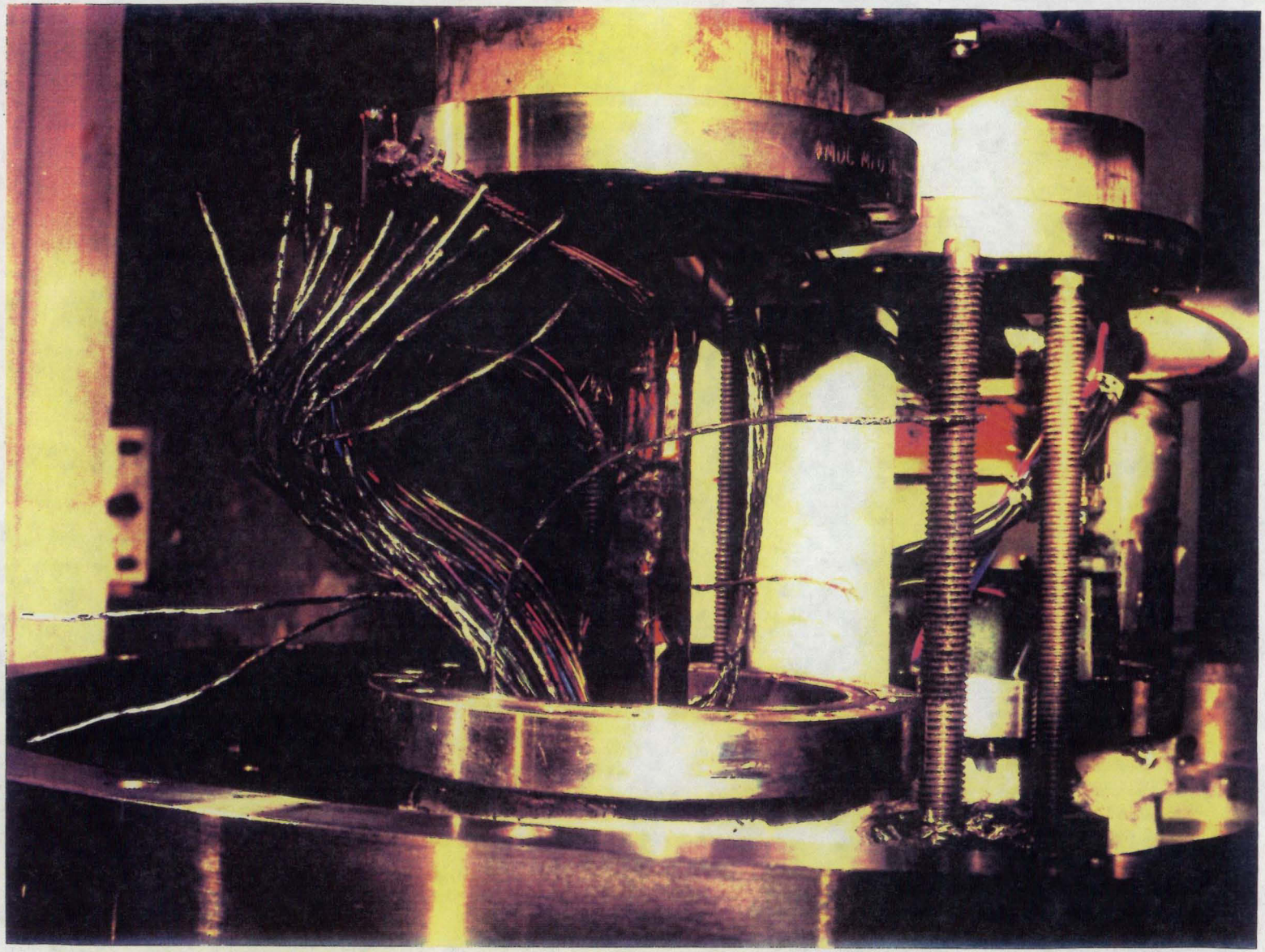


Figure 1. Magnet Interconnect on Test Stand Immediately After Failure.

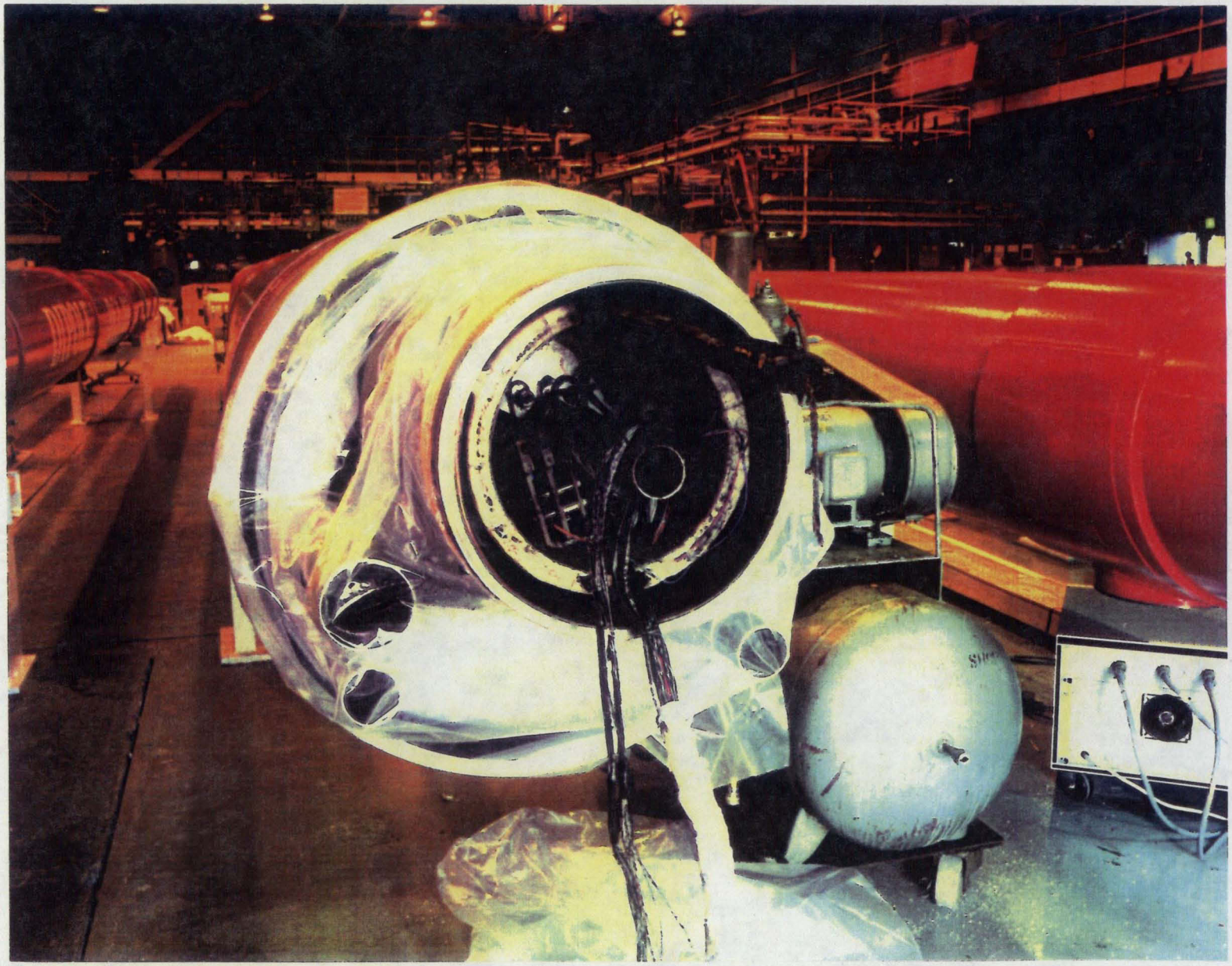


Figure 2. Return-End End Dome Removed.

Figure 3. Damaged Bus Exposed.

On August 13, 1992, DCA211 was once again on the test stand and ready for another round of cold-testing. The data presented in Appendix C includes all the quench performance to date. It is well worth noting that after all magnet repairs, the installation of a power bus crossover splice, and the thermal cycle the magnet's first quench was 7393 A, approximately 80 A off the plateau, which was achieved on the subsequent quench run. These results were most gratifying to all involved, and we are grateful to the entire failure-analysis team for their efforts.

— *C. Arden*

REFERENCES

1. W. Clay, J. Cox, and R. Thome, *Design of a Thermal Expansion Joint for the SSC Magnet Leads,* SSCL-382, March 1991.

Appendix A
BNL Electrical/Testing

This note is meant to supplement the memos already issued by E. Willen and J.G. Cottingham regarding the bus quench in DCA211 and it includes information derived from discussions with J.G. Cottingham concerning the electrical nature of the event. Here, plots of the relevant test parameters during the event are presented and unusual waveform features in the data are pointed out. As discussed in the notes mentioned above, a section of the negative superconducting bus on the feed can side of the internal loop expansion joint went normal at 6448 A during a ramp at 50 A/s to quench. That section, along with the rest of the superconducting bus work, is shown schematically in Figure 1 [shown here as Figure A.1], simplified from the electrical drawing 30E–00.137. This drawing shows the locations of the various voltage taps characterizing the behavior of the superconducting bus work, including expansion joints, during a quench. These taps are in addition to the 45 taps located in each inner coil of the magnet and the main taps which give the voltages of the four quarter coils. Each pair of taps gives the voltage of a section of bus and the voltage signal from each section is input into a pre-amplifier and acquired by a fast data logger module. The entire bus work is monitored in this way, each logger channel exhibiting the voltage from an adjacent section of cable. Table A.1 lists all fast logger channels which acquire the signal from the sections of the bus work depicted in Figure 1. With a 2 kHz sampling frequency and a record length of 4096 data points per waveform, data is acquired by the logger from about 760 ms before the quench detector trip (t=0) to about 1300 ms after, for a time domain of about 2 s.

TABLE A.1. VOLTAGE TAP SECTIONS AND FAST LOGGER CHANNELS FOR SUPERCONDUCTING BUS WORK (SEE FIGURE A.1)

CHANNEL #	TAPS	DESCRIPTION
112	W1–L1	Gas-Cooled Lead (+)
113	L11–W2	Gas-Cooled Lead (–)
114	L1–L2	Mini-Expansion Joint (+)
115	L10–L11	Mini-Expansion Joint (–)
116	L2–L3	Superconducting Bus Section
117	L9–L10	Superconducting Bus Section
118	L3–A	Superconducting Bus Section
119	L8–L9	Superconducting Bus Section
120	E–L6	Superconducting Bus Section
121	L6–L9	Superconducting Bus Section
223	L3–L4	Superconducting Bus Section
224	L4–L5	Expanded Joint
225	L5–0A	Superconducting Bus Section
507	L7–L8	Expansion Joint
508	L6–L7	Superconducting Bus Section

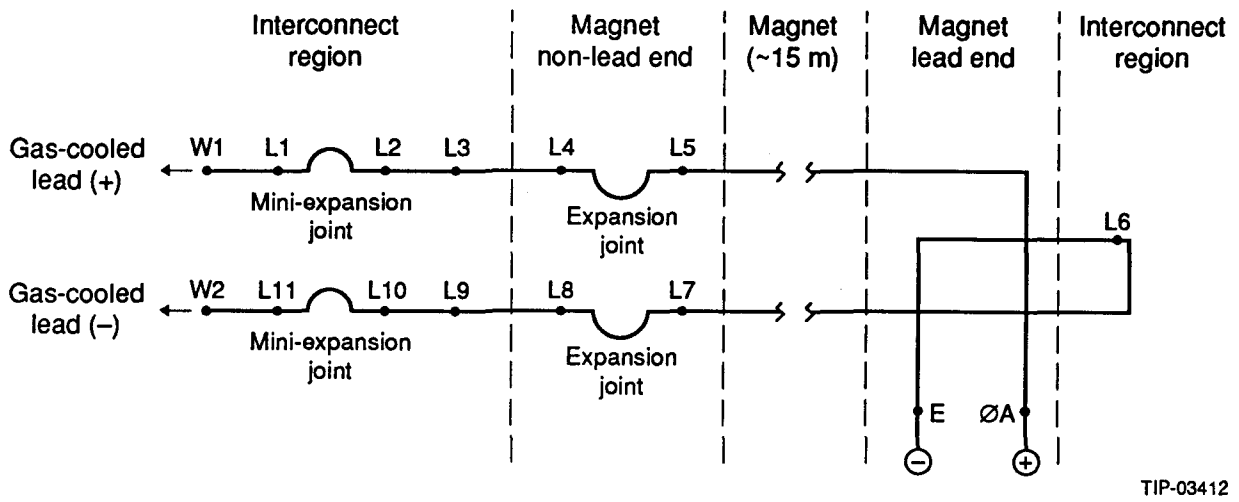


Figure A.1. Electrical Schematic of Superconducting Bus Work Voltage Taps.

In Figure 2 [not included here], logger channel 119 (tap section L8–L9) shows a voltage already saturating the pre-amplifier (>1V) out to 760 ms before the quench detector tripped the data loggers and shut the power supply off. It is not possible to obtain any information about this voltage except that the L8–L9 section, which is part of the bus in the upper wiring chamber leading into the feed can and on the feed can side of the expansion joint (described by J.G. Cottingham in his report), was already normal at –760 ms and clearly was normal for a significant amount of time before that. Unfortunately, the 2 s time domain of the data acquisition system does not allow a determination of the actual quench onset time, but no other section showed a signal start earlier than L8–L9. It is therefore reasonable to conclude that the quench started in that section, and inspection of that section in the wiring chamber did show significant damage, as described by E. Willen. Figure 2 also shows the voltages generated in the sections adjacent to quench start section L8–L9, and it can be seen that the expansion joint section L7–L8 (Ch. 507) starts to go normal at about –760 ms. The other adjacent section L9–L10 (Ch. 117), on the opposite side, shows a slight increase in voltage at about –300 ms. At –83 ms, both adjacent sections abruptly start exhibiting random high frequency noise spiking (hash), which is characteristic of electrical arcing and therefore represents the start of arcing events internal to the bus and between the two buses that led quickly to the destruction of that section of bus work. In fact, all other voltage tap signals show this noise at –83 A/s due to inductive coupling throughout the bus and the magnet coils. The amplitude of the noise in each section depends on the length of the cable in that section. For comparison, Figure 3 [not included here] shows the voltages of the same three channels 119, 507, and 117 during a normal spontaneous magnet quench (the previous quench #5 in DCA211) which indicate small microvoltages induced by changes in current during the magnet quench in the upper inner coil pole turn right straight section.

Figures 4 and 5 [not included here] show the power supply voltage and current, respectively. The power supply voltage is seen to increase during the 50 A/s ramp, in response to the resistance increase in the L8–L9 bus section as the quench propagates. At –83 μs, the onset of the arcing is seen. The same effect is seen in the power supply current, and an abrupt drop in current is seen at t=0, where the power supply shuts off.

Figure 6 [not included here] shows the four quarter coil voltages, which exhibit the same inductively generated arcing noise starting at –83 μs. It is seen from the plots of the quarter coil voltages that, even though the power supply current shut off at t=0 (Figure 5), current through the magnet persisted for about 500 ms due to shunt arcing across the positive and negative buses. At 80 ms, the strip heaters fired off, as they are supposed to, and safely quenched the magnet. There is no indication of any spontaneous quench in the coils.

The power supply ground signal in Figure 7 [not included here] shows arcing noise at –83 μs with a negative spike (>10 A). This noise seems to be largely inductive, but the spike could indicate some conduction to the walls of the wiring chamber by ionized gas generated by the arcing.

Temperature and pressure data during the ramp are also provided but are not conclusive. Though the main lead pot temperature sensors and the warm pressure transducers indicate possible heating effects as much as 30 s prior to the quench detector trip, it has been calculated by J.G. Cottingham that the conductor could not have survived more than 6 s after quench onset.

A study of high ramp rate quenches in a previous 15 m dipole DCA10 show no effects in the bus that might indicate a possible dI/dt heating contribution.

—J.F. Muratore
BNL
April 16, 1992

Appendix B
MIT Analysis/Testing

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Telephone: 617/253-8100

May 7, 1992

Dr. Ronald Scanlon
Lawrence Berkeley Laboratory
One Cyclotron Road
Berkeley, CA 94720

Dear Ron:

Thank you for the opportunity to visit BNL on May 5, 1992 to meet with your committee, to discuss some of the features of the SSC dipole bus design and manufacture, and to learn about the circumstances surrounding the bus burn-out at BNL on April 8, 1992.

Enclosed you will find a copy of the viewgraphs that we used at the meeting. I believe that they are also contained in the large pack of material that we forwarded to Wayne Clay on April 21, 1992 for use by your committee. We are reviewing the information that we brought back and will forward our thoughts to you in the near future on a possible testing program to investigate the limits of bus performance.

Meanwhile, we offer the following comments on the bus design and intended operation:

<u>Design Criteria-Decay Time Constant & Threshold Voltage</u>

Early in the bus design activity (mid 1990), there was a requirement for the bus to be able to withstand a current decay with a time constant of 36 s. This was retained through the Conceptual Design Review at FNAL in December, 1990, when it was recognized by the reviewers to be overly conservative.

Discussions then occurred in the December, 1990, to March, 1991 time frame, for which I have notes in my telephone log, indicating estimates for current transfer out of the bus on the time scale of 0.1-0.2 s when magnet protection circuits were activated, and indicating a resistive threshold voltage detection capability for the bus circuitry of at least 0.25 V. This resulted in a memo to MIT from SSCL, to use conservative values for bus design, that is, specifying a decay time constant of 2 s, with discharge to be activated following a threshold voltage of 0.5 V measured across the bus for detection of a propagating normal zone. The memo also directed MIT to use an energy margin requirement (stability) for design purposes of 240 mJ/cm of bus length.

Design Criteria-Stability

The stability requirement was established at 240 mJ/cm of length based on conservative estimates of the maximum possible stick slip event. Early in the design process, this was postulated as involving the sudden relative motion (5 cm) of bus metal relative to the surrounding insulator pultrusions using the maximum projected thermal contraction difference between the materials. Measurements of actual thermal contraction coefficients on materials in the bus since the requirement was established indicate that it could probably be expected to be 70 mJ/cm as a maximum in place of the 240 mJ/cm.

A test program on six different bus configurations, including the final design, with full scale cross-sections and currents, was performed at MIT as outlined in our meeting. Measured stability margins for the buses ranged from 175-280 mJ/cm. We also tested samples with unsoldered lengths of several inches between braid and cable and found the stability to disturbances introduced at the braid surface to be reduced by about 15%.

The bus (and magnets) operate in supercritical helium, hence, there are no distinct liquid and vapor phases. It is designed to be stable to transient thermal disturbances. The high energy margin in this design is achieved by using the braid on the surface of the superconducting cable to provide a high local reservoir of helium and a large surface area for transient heat transfer to the helium. Alternate designs with parallel copper bars are typically not as stable because they have reduced surface area, but could be equivalent from a protection standpoint since burnout is a relatively long time scale event largely dependent on the cross-section of copper available.

Solder Bond

The superconducting cable in the bus is designed and manufactured with a solder bond to the copper braid on each side. Since the void volume within the braid is desirable from the stability standpoint, the amount of solder in the bond is controlled during manufacture by using a solder foil of specified thickness. A considerable testing and tooling development program was performed, as we described at the recent meeting, to evaluate the bond integrity and to verify that the void volume was retained as desired.

The bus is soldered along its entire length except for the ends. It is delivered by the manufacturer with a relatively long length extending from each end to facilitate joining to interconnects or leads. These extensions are intentionally not bonded together to allow bending of the bus components into the required geometry. The geometry is well defined for the connections to the magnet coil leads and was considered in the development of the soldering fixtures in this area. It is still under development for the interconnect region. The intent of the design is for the cable and braid to be soldered together in the joint areas wherever possible when the bus is installed.

Protection

The amount of copper in the bus cross-section will not allow operation in the normal state for extensive time intervals without damage. It is designed to be discharged when the bus voltage reaches 0.5 V and arguments can be made that this voltage should be lower to expand the range

of operating currents over which the bus can be protected with greater confidence.

Estimates done in the usual way, assuming an adiabatic process and the heat capacity of the metals alone (frequently called a MIITS calculation), will lead to a lower bracket on the time to burnout of the order of 6 s and is strongly dependent on the current level. In an actual burnout, as experienced at BNL, the time to burn out would be expected to be substantially longer because: 1) the time scale is such that the adiabatic assumption is overly conservative, 2) there is substantial thermal capacity available in the heat of fusion of the metals and the melting and burning of the insulation, and 3) there may be, as in the BNL case, substantial cooling available from the rapidly flowing helium near the lead connection.

Normal Zone Propagation

Normal zone propagation speeds for the bus were derived in some of our tests and, as shown in our meeting, are of the order of 0.3 m/s when the current is 5000 A. We will proceed with an estimation of the propagation rate at the time of the burn out, based on the data we received from BNL which shows a rising voltage between the voltage taps at each end of the expansion loop prior to burnout at a level of about 0.3 V. We also note that the voltage across a larger section of the bus was saturated at more than 1 volt for a substantially longer time before burn out.

Charge Rate Sensitivity

We have reviewed our data, as mentioned in our meeting, and found that the rate of current ramp up in our tests was typically in the range of 150-200 A/s. This is substantially higher than the rates that were in use at BNL. We never observed a bus quench in any of the configurations tested that could be attributed to anything other than a heat pulse deliberately triggered into the bus by us.

We also note, as mentioned in our meeting, that the lead configuration for our tests always involved maintaining the cable to braid solder joint up to the power lead connection. We consider this to be good practice and believed it to be standard procedure at the labs. However, this was not done in the BNL test.

Future Bus Testing

The bus is designed to be stable relative to disturbances below a given size and the fact that they have operated well at BNL up to the incident on April 8 and at FNAL, is evidence of the ability of the bus to withstand the disturbances associated with usual operating conditions. However, if a normal zone does propagate in a bus, it must develop sufficient voltage in a short enough time to allow detection, reaction, and circuit discharge before the bus or components are damaged. A bus with braid and/or copper bar must be monitored and discharged when the design threshold voltage is reached to avoid damage.

The selection of the voltage level at which discharge will be triggered is critical to both safety and machine availability. At high operating currents (about 5000-7200 A), the trigger voltage can be 0.5 V, but a lower value would be desirable and should be achievable. If the trigger voltage

is set too high, it may not be achieved in sufficient time to prevent bus damage through local overheating. In view of the experience at BNL where the bus current was maintained even though higher voltages were recorded, it would be useful to investigate the limits experimentally in a testing program. This should be based on present system design constraints on the expected power lead connection geometry, circuit discharge time constants and threshold voltages. We will give more thought to an appropriate testing program and send you a memo on the subject in the near future.

I hope the above comments are helpful. Please call if you would like to discuss this further.

Sincerely,

Richard J. Thome

cc: D.B. Montgomery, MIT
W. Clay, SSCL
J. Zbasnik, SSCL
R.J. Camille, MIT
J.R. Hale, MIT

Thome
MIT
1/9/92

EXPERIMENTAL PROGRAM OVERVIEW

- Bus Stability and Quench Simulation
- Bus Lap Joint Resistance
- Lap Joint Mechanical Strength
- Differential Thermal Contraction of Bus Components
- Fatigue in Expansion Loop Insulation Assembly
- Fatigue in Bus Conductor (early configuration including Cu bar)

Appendix C
Quench Performance Data

Appendix C provides additional quench performance data in Figures C.1 and C.2 and in Table C.1.

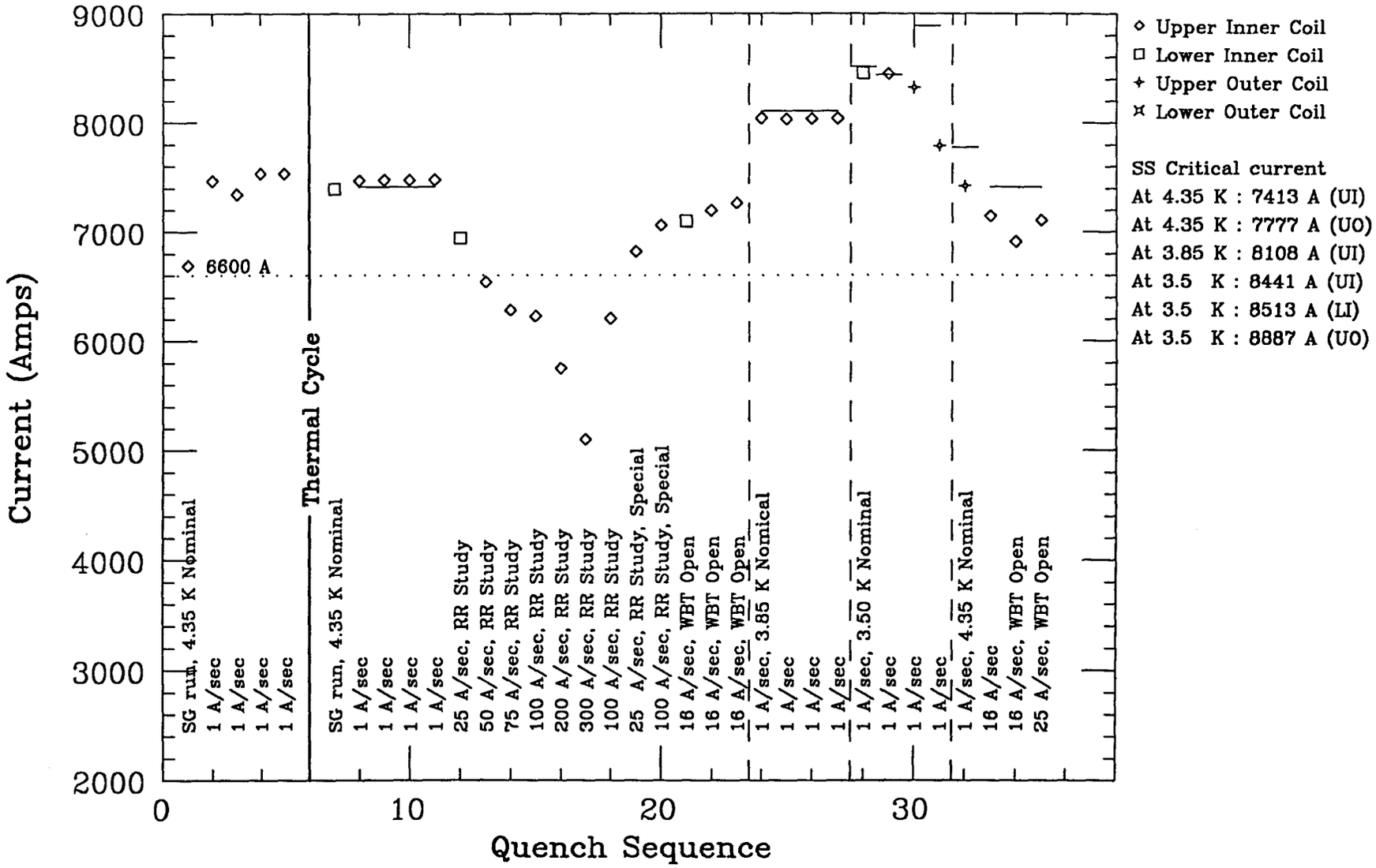
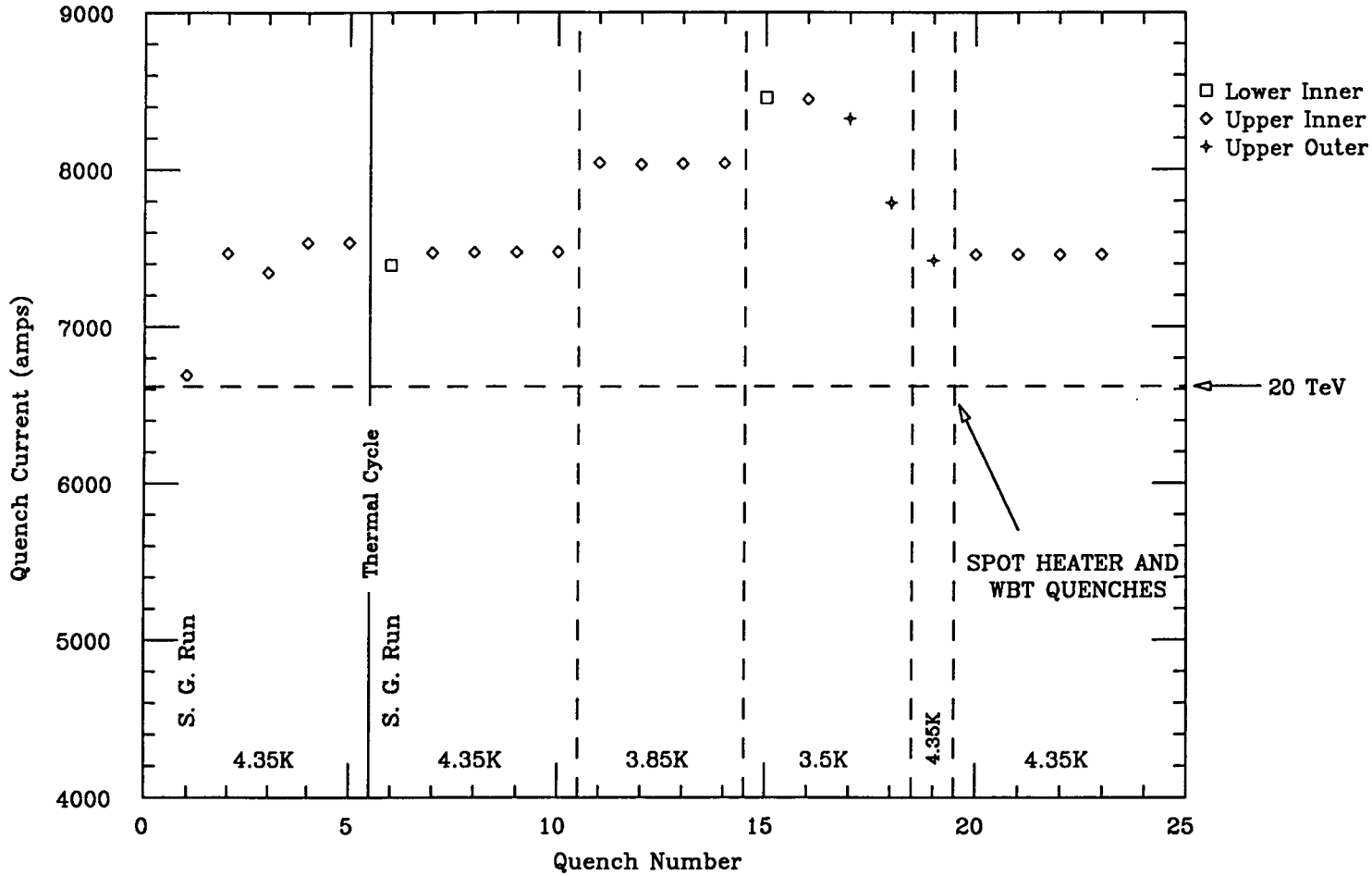


Figure C.1. DCA211: Current at Quench.



Note: Unless otherwise specified, the ramp rate was 16A/s to 6500A, 7000A, or 7500A, a 10 min wait, then 1A/s to quench.
Magnet was at room temperature for four months during the thermal cycle.
Ramp rate study quenches and quenches with the warm bore tube are not included in this plot.

Figure C.2. DCA211 Quench Test.

TABLE C.1. DCA211 QUENCH SUMMARY.

QUENCH #	RUN #	RAMP (A/s)	T(LE) (K)	T(RE) (K)	CURRENT (A)	MIITS	COIL	LOCATION	VELOCITY (m/s)
T = 4.35K (nom) Iss(4.35K) = 7449A									
1(a)	28	1	4.270	4.319	6692	14.667	UI	multiturn section, closer to lead end	
2	29	1	4.266	4.313	7469	13.710	UI	pole turn left strt sec, near return end	128
3	31	1	4.257	4.271	7346	14.126	UI	same as quench #2	114
4	32	1	4.254	4.262	7535	13.519	UI	pole turn right strt sec, close to middle	129
5	33	1	4.257	4.261	7535	13.562	UI	same as quench #4	127
(e)	35	50	4.258	4.262	6448			superconducting bus	
Thermal Cycle (see note e) T = 4.35K (nom)									
6(a)	56	1	4.290	4.308	7393	12.978	LI	pole turn right strt sect, toward lead end	118
7	57	1	4.295	4.314	7472	13.502	UI	same as quench #2	128
8	58	1	4.289	4.309	7476	13.520	UI	same as quench #2	127
9	59	1	4.291	4.308	7476	13.496	UI	same as quench #2	127
10	60	1	4.288	4.307	7478	13.507	UI	same as quench #2	126
Ramp Rate Study T = 4.35K (nom)									
11	62	25	4.290	4.306	6942	13.057	LI	multiturn section toward return end	
12	63	50	4.289	4.305	6540	13.235	UI	multiturn section toward return end	
13	64	75	4.288	4.304	6284	13.048	UI	same as quench #12	
14	65	100	4.290	4.304	6227	12.970	UI	same as quench #12	
15	66	200	4.288	4.303	5754	12.288	UI	multiturn section	
16	67	300	4.288	4.304	5103	13.061	UI	ramp section 19H-19G, close to tap 19G and 1.7" inside G10 box	10
17	68	100	4.287	4.303	6208	12.922	UI	same as quench #12	
18(g)	69	100 /25	4.290	4.303	6820	13.042	UI	multiturn section toward lead end	
19(h)	70	4/ 100	4.288	4.303	7061	12.967	UI	multiturn section toward lead end (same as quench #18?)	

9-10-92
(updated 9-25-92)
J. F. Muratore
Brookhaven National Lab

TABLE C.1. DCA211 QUENCH SUMMARY (CONT.).

Warm Bore Tube T = 4.35K (nom)									
20	86	16	4.296	4.325	7097	12.651	LI	multiturn section toward return end (same as quench #11?)	
21	92	16	4.298	4.322	7194	12.762	UI	multiturn section toward lead end	
22	103	16	4.299	4.326	7264	12.889	UI	multiturn section toward return end	
T = 3.85K (nom) Iss = 8058A									
23	111	1	3.811	3.847	8045	14.313	UI	pole turn right strt sec, toward return end	125
24	112	1	3.811	3.846	8034	14.157	UI	data not available (same as quench #23?)	
25	113	1	3.811	3.846	8038	14.203	UI	same as quench #23	123
26	114	1	3.801	3.831	8042	14.153	UI	same as quench #23	122
T = 3.5K (nom) Iss = 8441A									
27	117	1	3.471	3.508	8455	12.948	LI	pole turn short strt sec, 0.8" outside edge of G10 box	59
28	119	1	3.470	3.505	8448	13.281	UI	pole turn right strt sec, close to middle	127
29	120	1	3.470	3.507	8323	13.363	UO	upper outer coil	
30	121	1	3.464	3.507	7789	13.556	UO	upper outer coil, toward lead end	
T = 4.35K (nom)									
31	125	1	4.272	4.299	7422	12.167	UO	upper outer coil, toward lead end	
32(k)	136	16	4.285	4.311	7146	12.712	UI	multiturn sect, toward lead end	
The following series of quench tests (quenches 33 - 42) were done in conjunction with magnetic measurements investigating eddy current effects. Warm Bore Tube 4.35K (nom)									
33	141	16	4.286	4.331	6912	13.091	UI	multiturn section toward lead end	
34(i)	142	75/ 25	4.287	4.326	7107	12.832	UI	multiturn section toward lead end	
35(i)	144	25/ 25	4.289	4.336	7046	12.904	UI	multiturn section toward lead end	
36(j)	145	-4885	4.288	4.335	~5000		UI	ramp-splice section (j)	
37	150	75	4.291	4.383	5985	12.694	UI	multiturn section toward lead end	

TABLE C.1. DCA211 QUENCH SUMMARY (CONT.).

38	151	75	4.290	4.377	6003	12.714	UI	multiturn section toward lead end	
39	152	75	4.290	4.380	6011	12.700	UI	multiturn section toward lead end	
40	153	75	4.291	4.382	5984	12.696	UI	multiturn section toward lead end	
41	154	50	4.289	4.384	6110	12.818	UI	multiturn section toward lead end	
42	155	25	4.291	4.385	6109	12.963	UI	multiturn section toward lead end	
T = 4.35K (nom)									
43	156	1	4.291	4.318	7461	12.584	UI	same as quench #28	123
44	157	1	4.292	4.318	7461	12.595	UI	same as quench #28	122
45	158	1	4.292	4.317	7460	12.611	UI	same as quench #28	122
46	159	1	4.289	4.309	7460	12.630	UI	same as quench #28	121
47(k)	160	4	4.292	4.319	7362	11.911	LI	multiturn section	

Notes:

a) Strain gauge run-to-quench. The ramp rate between current steps was 16A/s to 6500A, then 1A/s to quench.

b) For tests at 1A/s or 4A/s, the current was ramped first at 16A/s to 6500A or 7000A, paused for 10 minutes, then ramped at 1A/s or 4A/s to quench.

c) During tests up to quench #22, temperatures recorded above are from the carbon-glass sensors TCG1 (lead end) and TCG3 (non-lead end), which are mounted in collar packs at the coils. After quench #22, including tests at 3.85K (nom) and 3.5K (nom), temperatures recorded are from the diode sensors T3 (lead end) and T9 (non-lead end), mounted in the end can (magnet lead end) and lead can (magnet non-lead end), respectively. This change was necessary when the carbon-glass sensors became unreliable. All temperatures recorded above are taken from the control room log book entries. Note that cold helium gas enters the magnet at the lead end and warmer gas then leaves the magnet at the non-lead end.

d) There is evidence that the magnet temperature was warmer during the first three quenches. Slow logger temperature data indicates that the the magnet was still cooling down during this time. Possible causes of this include an unexpected refrigerator shutdown on the day before testing started and a sudden warmup of the magnet between quenches #2 and #3 due to a leak in the vacuum when an indium seal failed. This might explain the unusually low first quench and the erratic behavior of the next two quenches.

e) This quench occurred in a superconducting bus far from the magnet leads and therefore did not involve the magnet itself. Since the bus was damaged, however, the tests had to be ended and the system warmed up. The magnet was subsequently at room temperature for about four months while repairs were effected and other magnets were tested in the horizontal bays. The bus quench and warmup occurred on April 8 and testing resumed Aug. 13.

TABLE C.1. DCA211 QUENCH SUMMARY (CONT.).

f) Quench plateau at 4.35K after the thermal cycle is about 60A lower because the magnet temperature is higher by about 40mK.

g) For quench #18, the current was ramped at 100A/s to Iq(100)-75=6152A, then at 25A/s to quench. Iq(100)-50=6177A was tried in quench #17, but the quench occurred while still at 100A/s due to overshoot in the power supply.

h) For quench #19, the current was ramped at 4A/s to Iq(100)+50=6277A. then at 100A/s to quench.

i) For quench #34, which was with the bore tube warm, the current was ramped at 75A/s to 6000A, held at 6000A for 5 min, then ramped at 25A/s to quench. For quench #35, which was also with the bore tube warm, the current was ramped at 25A/s to 6000A, held there for 5 min, then ramped at 25A/s to quench.

j) Quench #36 occurred at approximately 5000A after a power supply shutoff from 6600A. The initial negative ramp rate was 4885A/s. The bore tube was warm during this event. There is evidence from the fast data that the quench location was in the upper inner coil ramp-splice section, but this is not completely certain due to so far unexplained ambiguities in the fast data. The magnet was later tested with an initial negative ramp rate of 548A/s from 6600A, with the bore tube sealed; there was no quench.

k) Quenches #32 (16A/s) and #47 (4A/s) were done as part of the ramp rate study.