SSC-N-437
January 1988

MAGNET DD000Z REVIEW COMMITTEE

Following the failure of the lower inner coil of magnet DD000Z on November 3, 1987, a committee was formed on November 11 and charged with the following objectives:

To review the events leading up to and including the failure of the coils of magnet DD000Z. The intent of the review will be to determine the cause of the failure and to make recommendations to reduce the likelihood of such failures in the future.

Given the fact that this is the first long magnet to be disassembled, the committee may uncover leads which point to other problems. The committee should follow up on these leads.

The commitee should prepare a plan to serve as an initial guide for the disassembly and provide guidance as the disassembly progresses."

Members of the committee are:

R. Coombes (Chairman)	CDG
K. Mirk	CDG
J. Tompkins	CDG
R. Lundy	FNAL
J. Zbasnik	LBL
W. Schneider	BNL
P. Wanderer	BNL

The committee held its first meeting at FNAL on 17 &18 November to review the record of events leading up to the failure and to establish an initial disassembly procedure. This was followed by further meetings at FNAL, BNL, and CDG, leading to this final report.

Committee activities included interviewing personnel who had been involved in the design, assembly and testing of DD000Z, and reviewing all documents relating to the magnet and its failure.

The intention of the committee was to report factual findings, to consider well founded hypotheses, not to consider conjecture and to avoid speculation.

Index

REPORT OF THE MAGNET DD000Z REVIEW COMMITTEE

I. General Description and Assembly

Introduction

Magnet DD000Z was the fourth in the series of 17 meter long development dipoles to be built and tested as part of the magnet research and development program for SSC main ring bending magnets.

The magnet was designed to conform largely to the Systems Requirements prescribed by the Central Design Group in document SSC-MAG-D-101. In this document the operating field is specified as being 6.613 T at 4.35 K.

The "cold mass" of the magnet, consisting of the assembly of yoke, collars and coils contained within a 10.75-inch diameter stainless-steel skin, was designed built, and warm tested at Brookhaven National Laboratory. See Fig. ____.

The completed cold mass was shipped to Fermi National Accelerator Laboratory where it was installed in a FNAL designed and constructed cryostat which was then mounted on test stand #4 of the Magnet Test Facility at FNAL, for cold testing (Fig. ____).

Following a series of training quenches, the magnet reached 6290 A, 98% of the estimated short sample current limit. After 9 quenches the magnet started developing unusual behavior which became more noticeable over the next 4 quenches, culminating in a quench and simultaneous rupture of the beam pipe, while ramping through 3135A following quench #13.

The magnet assembly was removed from the test stand and following removal from the cryostat, the cold mass was returned to BNL for inspection and further disassembly under the supervision of this committee.

General Features of DD000Z

As might be expected of the fourth magnet in an R&D series, magnet Z shared many features with earlier long magnets, but was also unique in many ways.

The first two magnets, D0001 and 2 had been built with coil ends that flared out in a dog-bone configuration. The coil ends of Z, like precursor X, were 'straight,' forming a racetrack-like shape (Fig. ____). The collars that constrain the coils were made of stainless-steel, a feature common to all four magnets; however in the case of magnet Z, in order to improve field uniformity, a newly designed coil cross section, C-358A (Fig. ____) was used, and to increase mechanical rigidity the collars were spot welded in pairs prior to assembly.

The inner coil, was wound with a cable of 1.55:1, copper to superconductor ratio. All coils in this magnet used upgraded pole spacers made of machined G-11, and all coil ends were 'filled' with alumina-loaded epoxy. The low carbon steel laminations forming the magnetic yoke of magnet Z were adapted to suit the smaller tabs on the new C358A collars and also to provide space for longitudinal warm up heaters. To reduce the peak magnetic field in the critical end regions of this magnet, the yoke laminations were replaced with nonmagnetic stainless steel laminations at the ends, the stainless steel extending about 2-1/2" over the straight section of the coils.

Magnet Z was also used as a test vehicle for newly designed superconducting coils to compensate for sextupole, octupole and decapole field distortions. These trim coils were mounted on the outside of the beam pipe. The beam pipe itself was unique in that a 12-foot long section in the center had been internally copper plated, again as an initial test of a completely internally plated beam pipe, a feature that will be required in all production magnets.

Instrumentation

The normal complement of instrumentation included 5 voltage taps which provide signals to the quench protection circuitry (Fig. ____), strain gauge load cells (full bridge) reading the azimuthal prestress of the inner and outer coil, a readout of the cold pressure at the center of the magnet using a piezoelectric transducer, and sensors at both ends of the cryostat recording temperature. Other standard instrumentation included pressure sensors in the interconnect cans at both ends of the cryostat.

In addition, magnet Z was fitted with a pair of extensometers (linear potentiometers) to measure relative linear motion between the coil end and the end plate, at the return end of the magnet (Fig. ____). The second unit of the pair was inactive and provided temperature compensation. This device was sensitive only to motion of the coil away from the end plate. Motion of the coil end in the outward direction, which would tend to deflect the end plates outwards, was monitored by strain gauges mounted on the end plates. In each case a pair of orthogonal gauges was attached to the plate, with a third, strain free gauge, for temperature compensation located nearby (Fig. ____).

The end plates themselves were made of 3/4" thick stainless steel discs cut in half at the equator. (The 'cut' was actually 3/4" wide.)

At the 'Feed End' of the magnet, where electrical and cryogenic connections are made, the strain gauges described were mounted only on the top half end plate. At the other, 'Return' end of the magnet where space limitations were not so severe, strain gauges were provided on both top and bottom end plate halves.

Historical Outline

The following summary shows the time frame for assembling and testing the magnet:

First collaring	30 April 1987
First assembly complete	15 June 1987
Disassemble, pot ends	23 July 1987
Open 2 m at lead end to repair short, then ship	1 September 1987
Install in cryostat and move to MTF	5 October 1987
Cooldown	18–20 October 1987
Quench #1	22 October 1987
Quench #9–12	27 October 1987
Quench #12(a) (lead event #5) and #13	28 October 1987
Quench #14	3 November 1987
Remove from cryostat	12 November 1987
Ship cold mass to BNL	21 November 1987
Diassemble cold mass	2–9 December 1987

Notable Incidents During Assembly and Test Preparation

When the magnet was first collared in April 1987, a turn-to-turn short was detected at the lead end of the midplane turn of the lower inner coil, the short was repaired and the collaring proceeded. A few days later a second similar short occurred at a location near the first one.

This second short was also repaired and the assembly of the magnet was completed, the cold mass being ready for shipment to FNAL on June 15th as scheduled.

In addition to the long magnet program, BNL was also building and testing short 1.8 meter magnets, and in early June the performance of one of these short magnets, DSS2 had improved dramatically, following the implementation of a new procedure for stabilizing the ends of the magnet by filling the ends of the coils with alumina-loaded epoxy. Based on this result, it was decided to carry out the same procedure on magnet Z.

The magnet skin was therefore cut open, the coils uncollared, the ends of the coils impregnated with alumina loaded epoxy, the new style machined G-11 pole spacers (Fig. ____) were installed in place of the earlier molded spacers, and the magnet reassembled.

Several days after the magnet skin had been rewelded, a turn to turn short occurred, once again near the same location on the lower inner coil. This time, in order to effect a repair it was necessary to cut open a section of the skin, including approximately the last 2 meters at the feed end. Following the removal of the yoke sections, the end of the magnet was uncollared and the upper coil raised ('fish-mouthed') so that the repair could be made.

All of the shorts were attributed to the excessive pressure exerted on the coil insulation during collaring due to a build-up that had occurred where the copper field shaping wedges were butted against the wedge tip at the end of the coil straight section. In each case, additional insulation had been wrapped around the joint between the wedge and the wedge tip, such that approximately .015" of added insulation occurred at each of the 3 wedges. This is a very delicate area as it also marks the transition from the long 'straight section' to the curved 'end' of the magnet. To help compensate for the .045" tolerance build-up, the pole shims in the last collar pack had been reduced in size. The pole shim can be seen in Fig. ____. However the improved G-11 pole spacers which were added when the end of the magnet was filled, and the width of which should have matched the dimension across the pole shims, was installed 'as built' with no reduction in size to correspond to the reduced size of the pole shims. The result was a step of about .016" between the pole spacer and the pole shim, on each side of the pole. This defect was rectified at the lead end, by reducing the size of the pole spacers when the final short was repaired. At the return end no shorts had been detected and due to the difficulty and risk associated with cutting open that end of the magnet, the pole spacers were left uncorrected.

Following the final repair, warm magnetic measurements were carried out at BNL using a 'Mole.' The mole is used to measure multipole components of the field while the magnet coils are energized with a current of 10 Amps and is drawn through a stainless steel warm bore tube of 1.166 O.D. that is inserted inside the beam pipe. No difficulty was noted in inserting the warm bore tube to make this measurement. Following shipment to FNAL the coil was again energized, and a vertical field sensing probe was used to measure the correct 'roll' orientation of the magnet prior to mounting it in the cryostat.

The FNAL vertical field sensing probe is wrapped with teflon tape to an O.D. of 1.290 inches which just provides clearance for sliding the probe directly into the beam pipe. In the case of magnet Z, however it was discovered that the probe could only with difficulty pass a region near the feed end of the beam pipe and could not pass beyond a region near the return end of the beam pipe. The internal restriction at the return end of the beam pipe which occurred about 8" from the return end was measured using an internal micrometer, see Fig. ____. The restriction at the feed end was approximately 17" from the end and could not easily be measured.

When the magnet was positioned on the test stand at FNAL, unusual difficulty was experienced in sliding the cold mass bellows into position for welding. At the time it was suggested that the magnet may not have been perfectly aligned with the stand, which could account for such difficulty. No further incidents could be attributed to this problem and no subsequent explanations were found for the difficulty.

An additional problem discovered after the arrival of the magnet at FNAL was that the negative power lead expansion loop was not seated properly in the G-10 rail provided for the lateral restraint of the bottom of the loop (Fig. ____). The expansion loop had been checked and found to be correctly mounted when the cold mass was shipped from BNL so presumably the displacement had occurred during shipping.

II. Magnet Testing at FNAL

Fermilab Test History

The mounting of magnet DD000Z on stand 4 took almost exactly two weeks from delivery of the magnet to the stand to the beginning of cooldown. This was followed by a 54 hour cooldown and two days of quench protection system checkout. Quench testing began 16 days after delivery of the magnet to the test facility. The magnet was quenched 13 times, with quenches 11–13 being at 97–98% of the calculated short sample limit. Quench #13 was accompanied by a trip of the ground current safety circuit: a ground fault occurred which drew an estimated 10 amps (the detection circuit output saturated at 5 amps). Following this fault, the magnet resistance to ground was measured to be several hundred ohms. Following several days of discussion and preparation (moving the system ground) testing resumed. The magnet was ramped to quench at 3135 amps at which time the beam pipe was ruptured.

Although the failure of magnet DD000Z resulted in a truncated test program, valuable data concerning the stress/strain state of the magnet was gathered in addition to the information from the quench testing. Specifically, the magnet end plates were instrumented with strain gauges allowing a measurement of the force transmitted by the coil during excitation. In this section, we present brief summaries of the test data: the quench current history, a discussion of quench position, and the mechanical state of the magnet from the strain gauge data. This will then be followed by a summary of the anomalies observed during testing: the power lead 'events' and the growth, observation of, and final effect of the ground current fault.

Discussion of 'Normal' Testing

i) Quench Current History. The quench current history of magnet DD000Z is shown in Figure ____ where we have plotted percentage of short sample current vs. quench number for the first 13 quenches. The short sample values have been calculated using the measured temperature values from the feed and return interconnect thermometers. The magnet like magnet DD000X trained slowly, but was nearly 'monotonic,' displaying little of the erratic quench current behavior observed in the first two long magnets. A summary of the quench data is given in Table I.

ii) Quench Position. An estimate of the longitudinal position of the quench origin is obtained from analysis of pressure transducer data. Pressure transducers are located in the feed and return end interconnect regions. The arrival time of the pressure wave from quench origin is determined for the transducers at each end of the magnet and these times, labelled t_{feed} and t_{return}, are plotted against each other. The sum of these two times should be a constant—the time for the pressure wave to travel the length of the magnet at the speed of sound in helium appropriate to the operating conditions (plus offsets corresponding to fixed lengths in the plumbing, etc.). Quenches originating near the feed end should have short t_{feed} and long t_{return}; similarly, those quenches originating near the return end should have short t_{return} and long t_{feed}.

A plot of t_{feed} vs. t_{return} is shown in Fig. ____. The regions of the plot expected to be populated by feed and return end quenches have been indicated with arrows; the straight line is drawn to guide the eye. The spot heaters were used to induce quenches at both ends of the magnet: these data are labelled 'NW' and 'SW' on the plot. The spontaneous quenches are labelled by their quench number; the point labelled 'PL' is a power lead 'event' (to be discussed below) which was accompanied by a real quench after detection. Note, no corrections have been applied for differences in quench generation times (the zero of the time scale is defined as the time when the appropriate safety circuit—in this case the Upper-Lower coil voltage difference—passes a predetermined threshold).

In contrast to magnet DD000X, the training quenches were not dominantly at the feed end—several quenches are clearly not associated with either end, and the later quenches (10 through 13) are all near the return end. The position of the last three quenches, 11, 12 and 13 is unusually stable and close to where the magnet failed.

iii) Strain Gauge Data. The instrumentation provided on magnet DD000Z is described in Section I. The strain gauge and extensometer information obtained during testing can be divided into three sections: behavior during cooldown, behavior during magnet excitation, and long term cumulative effects ('ratcheting').

The earlier program of testing long magnets had raised questions about the relative motion of the ends of the coils and the end plates during cooldown and energization. The extensometer data indicates that the coil and end plate did not separate at the return end. Figure ____ shows the extensometer data as a function of time during cooldown as well as the return end temperature measured by a carbon-glass resistor. The lower plot corresponds to the active gauge, the middle plot is the passive gauge, and the upper plot is the temperature. The only motion indicated by the active extensometer is exactly mirrored by the passive extensometer and thus is interpreted as imperfect temperature compensation with no real movement of the coil with respect to the end plate.

During cooldown the axial gauges on the end plates shown an increase in strain indicating that the end plates are pushed outwards by the ends of the coil. This is consistent with the lack of motion at the extensometers. During excitation, these axial gauges yield interesting results. If we plot the strain values prior to each magnet excitation, we can examine the cumulative effect of coil energization and quenching. The plots obtained for the two return end and one feed end gauges are shown in Fig. ____. There is clear evidence for 'ratcheting' throughout the life of the magnet, the strain in the end plates increasing after each quench, and remaining high even when the current is reduced to zero.

The two return end gauges show nearly identical behavior; the feed end gauge shows a comparable increase in strain, but the scale is dramatically different. (The large offset seen in the feed end gauge is attributed to problems with one of the bridge arms.)

The end plate strain gauges were added during the final assembly of the magnet and were not calibrated before installation. Estimates of the calibration give 113 $\mu\epsilon$ in each half plate for 1000 lb load applied to the full end. Thus the increase in strain observed at FNAL, of nearly 800 $\mu\epsilon$ corresponds to a 7000 lb force on the end plate.

To investigate hysteresis effects, data were taken at intervals during an excitation of the magnet to about 5800 amps between quenches 6 and 7. Unfortunately, a safety circuit tripped after a point at 3000 amps on the downramp. The end plate strain data taken to that point are shown in Fig. ____. It is clear in the plots that the strain is not returning to its initial value. The net change in strain after the excitation (and safety trip which fired the quench protection heaters) averaged about 30 $\mu\epsilon$. A further study of this effect was made by reading the strains before and after a magnet excitation from 0 to 5836 amps and back to 0 (without a quench); the change in strain averaged about 20 $\mu\epsilon$.

The load cells measuring the azimuthal prestress of the coils show a typical small loss in prestress during cooldown, and then very little change after the initial excitation of the magnet. The outer gauges remain roughly constant (one of them died after quench #5) while the inner gauges show initial erratic behavior through the first quench and then are roughly constant thereafter. The two inner gauges both show an increase in strain of about 800 $\mu\epsilon$,[2] following cooldown and initial excitation.

Summary of Test Results

The test results discussed above can be summarized as follows:

1) Magnet DD000Z trained slowly, but nearly monotonically, to reach currents near 98% of short sample and like DD000X, showed little of the erratic behavior of the first two long magnets.

2) Analysis of the longitudinal quench position showed that although the early training quenches were near the feed end, there were a significant number of training quenches not associated with either end of the magnet, again in contrast to the data available from long magnets D0002 and DD000X.

3) The last three quenches occurred at almost identical longitudinal positions and are thought to have occurred near or at the location at which the magnet failed, the return end of the lower inner coil.

[2] The 'old style' azimuthal gauges used on this magnet have been characterized as 'untrustworthy' (B. Schermer, internal memo); however, rough calibrations are one $\mu\epsilon$ corresponds to about 30 psi on an inner coil gauge and 20 psi on an outer coil gauge.

4) The end plate strain gauge data give a consistent picture of strain increasing with each magnet excitation indicating that the coil moves out due to the Lorentz force during excitation but does not fully return to its former position.

5) The azimuthal coil gauges did not exhibit the ratcheting seen in the end plate gauges.

Discussion of Anomalies During Testing and Magnet Failure

1) *Power Lead Events*

The lead quench protection circuit, which was set at a threshold of 7 mV, was tripped five times by signals of unknown origin, causing what have been dubbed 'lead events'. In all cases, the voltage appeared in the negative lead in the region including the expansion joint and the 'through' and 'connected' buses which have a total length of 34 meters. Voltage taps which bracket the solder joint between the magnet lead and the supply lead showed no pre-trip voltage. The first event was at 3464 A, and subsequent events were at monotonically increasing current up to 6109 A. A plot of the safety circuit voltage versus time for a power lead event at 4708 amps is shown in Fig. ____. The voltage rises very sharply and then decreases; a true quench signal would have a slower rise and continued growth as the resistive region propagates through the coil. The Upper-Lower coil voltage difference signal for the first spontaneous quench, at 5009 amps, is displayed in Fig. ____. There is a clear difference in the behavior of these two examples.

The performance of the magnet during a lead event closely follows that occurring when the quench protection circuitry is triggered by an external source. This would seem to indicate that the voltage signal on the lead is generated by some mechanism other than the initiation of a quench.

2) *Ground Fault History – Growth of Ground Current*

The test of magnet DD000Z was terminated when a short from the coil to ground and a rupture of the beam pipe occurred during quench #14. This was preceded by detection of significant ground current during quench #13 and subsequent measurement of a resistive path from the coils to ground of a few hundred ohms. The short was detected by the ground current safety circuit which had been set at a threshold of 2.5 amps; the ground fault during quench #13 drew an estimated 10 amps (the analog converter recording this signal saturates at 5 amps). By reviewing the data from earlier quenches it has been possible to follow the evolution of the problem.

Beginning with quench #10, evidence is present in the data for "sparking" at the level of a few mA in the ground current detector.[1] The precursors to the major ground fault in quench #13 can be observed in both the plot of ground current and the plots of the individual quarter coil voltages. Figs. ____ through ____ show the ground current and quarter coil voltages (where $L\,\frac{dI}{dt}$ has been subtracted to give the resistive component) versus time for quenches #10 through #13. The zero of the time scale is set by quench detection (in this case, when the Upper-Lower coil voltage difference reaches .5 V). At earlier times there is considerable power supply noise on the signal; after quench detection, the power supply is shut off and the signal is much cleaner.

The data for quench #10 show a 60 mA spike in the ground current about 230 msec after quench detection. Looking at the quarter coil voltage plot, one sees a small 'glitch' at the same time. Quench #11 shows smaller ground current spikes of roughly 6–8 mA at times of ~180 and ~210 msec; there are corresponding small 'glitches' in the quarter coil voltages.

Quench #12 is the first to show dramatic evidence of the developing fault. The ground current plot shows continuous activity from about 170 msec until about 450 msec following quench detection. The quarter coil voltage data also reveal numerous spikes. Unfortunately, the system diagnostics were not sensitive to relatively low levels of ground current (the ~70 mA spikes are still well below the 2.5 A detection circuit threshold) and the inter-quench analysis procedure did not examine the voltage plots past 100 msec (initial resistance development) or the ground current plot.

[1] There is typically a very small 'spike' in the ground current signal at about 135 msec, which is the time at which the quench protection heaters are fired. These spikes are ignored in this analysis.

Quench #12 was followed by a 'power lead event' labeled quench file #30 (see Fig. ____) at a current of about 6100 amps. When the power lead safety circuit is tripped, the quench protection heaters are fired immediately which causes the outer coils to quench. The quench development induced by the heaters in the outer coils then typically takes 40–50 msec until appreciable resistive voltage is detected. However in this lead event, the lower inner coil begins to show resistive voltage before the outer coils. At the time, this was mistakenly thought to be propagation of the lead 'quench' through the lead and into the coil.[1] To test for heating and subsequent quench development from the negative lead splice, the magnet was ramped to 6000 A and held at that value for more than 10 minutes without incident.

Quench #13 at 6290 A, then followed with the massive ground fault which tripped the detection circuitry following quench detection. The voltage plots show evidence of severe sparking; the ground current plot saturates at 200 mA (a lower resolution ground current measurement saturates at 5 A.) Following this event, testing was suspended and an effort was made to determine the extent of the fault and how to proceed.

Measurements yielded values of the magnet resistance to ground of several hundred Ohms. Inductance ratio measurements placed the location of the ground (assuming a single ground fault), in the lower inner coil, 2% by inductance away from voltage tap "D" which is at the splice between the lower inner and lower outer coils. This is approximately equal to the calculated inductance fraction in the pole turn, suggesting that the fault was near the lead end. Examination of the voltage and pressure data from the power lead event which occurred just before quench #13 shows the lower inner coil quenching near the return end. If this unusual occurrence was caused by the presence of the (then unnoticed) ground fault, this would have placed the fault near the non-lead end. Attempts to measure the resistance of the ground fault as a function of voltage up to 45 V yielded values varying between 100 Ohms and 100 kΩ.

[1] The lead event occurred on the negative lead; the lower inner coil is connected to the *positive* lead not the negative lead as was understood at the time.

A panel of [redacted] at FNAL reviewed the evidence and concluded that it would be reasonable to move the system ground to the voltage tap nearest the estimated location of the fault (voltage tap D) and to proceed with testing. This was the procedure that had been followed during the testing of the first long magnet at FNAL when it developed a resistive ground fault.

The magnet was then grounded in this way giving a total of 226 Ohms in the explicit ground, and to increase it's stability the magnet was cooled to 3.3 K. It was estimated that the peak voltage at the ground fault would not exceed 50 V. The magnet was then ramped to quench at 3136 A with the simultaneous rupturing of the beam pipe. (The insulating vacuum is independent of the beam pipe vacuum and was unaffected.) Evidence for significant sparking exists in the coil voltage signals before substantial ground current developed, suggesting turn-to-turn as well as coil to ground shorts were present. The octupole trim coil was then found to be shorted to ground, suggesting that the beam pipe rupture was in the quarter of the magnet closest to the non-lead end, the region occupied by this coil. The ground current and quarter coil voltage plots for quench #14 are shown in Figs. ____ and ____.

The fact that a quench occurred at 3136 A was somewhat surprising: this is about one half of the current of the previous quench. Analysis of the voltage development prior to quench detection reveals a fairly linear initial growth rate for 30 or 40 msec. This can be seen in Fig. ____, which displays the Upper-Lower voltage difference.[1] If one estimates a quench velocity (assuming only 2 quench fronts in the region), a value near 20 m/sec is obtained. This velocity is similar to the velocity determined for previous quenches which occurred at much higher current.[2]

---

[1] This channel is used rather than the individual lower inner coil channel because moving the ground resulted in excessive noise.

[2] It is possible that the voltage growth is due to resistive growth of a fixed region due to heating rather than quench propagation. A second possibility is that a turn to turn short created a region where the current, through $L\frac{dI}{dt}$, has grown close to short sample.

3) *Power Lead Trip Following Quench #12*

As discussed in the previous section, a power lead trip occurred at a current of about 6100 amps during the magnet excitation that followed quench #12. This event was marked by what was considered an unusual development of resistive voltage in the lower inner coil. Interpretation of the data from this event is important in understanding the evolution of the ground fault following quench #13 so we examine it in more detail here.

In typical non-quench induced events, such as a power lead trip, there is no resistive voltage in the magnet coils until after the quench protection heaters have fired. The quench protection heaters are in contact with the outside of the outer coils and thus resistive voltage develops in the outer coils well in advance of the inner coils. Examples of quarter coil voltages developed by the quench heaters following lead events are shown in Figs. ____ and ____ which are the third and fourth power lead events during magnet DD000Z testing, occuring at a current of 4708 and 5436 amps, respectively. Recalling that for power lead trips the quench heaters are fired without delay, one sees voltage developing almost simultaneously in the two outer coils after about 50–70 msec, and the inner coils lagging by 50 to more than 100 msec, depending on the magnet current. The maximum voltage developed by the inner coils is typically less than about 1/3 of that reached by the outer coils. The patterns in the two plots are, as expected, quite similar: the outer coils lead and the inner coils follow. The relative times change as the magnet current (and thus quench velocity) increases.

In contrast, the voltage development observed for power lead event #5 (following quench #12), as displayed in Fig. ____, is strikingly different: the lower inner coil has clearly developed resistive voltage in advance of the outer coils. Examination of the upper-lower coil difference voltage (the normal quench detection circuit), shown in Fig. ____, does not reveal any voltage (quench) development prior to the trip (at time $t = 0$). Thus the voltage in the lower coil clearly developed after the trip and, since it precedes the voltage induced in the outer coils, it could not have been caused by the quench protection heaters.

The presence of a turn-to-turn short would explain this behavior. The shorted turn(s) could be driven to quench by the increasing $\frac{dI}{dt}$ after the power supply is shut off. At 20 msec after the trip $\frac{dI}{dt}$ = −400 amps/sec, (25 times the ramp rate); the measured $\frac{dI}{dt}$ is shown in Fig. ____. Heating at the short could both induce the quench and further weaken the insulation.

Further consistency derives from the quench location estimated from the pressure data. The raw t_{feed} and t_{return} values placed the origin near the return end. However, the data should be corrected with respect to the normal quench data since conditions are different. A power lead trip fires the quench heaters without a delay and the 'late' time signal—in this case t_{feed}—which has to travel nearly the full length of the magnet, can be masked by the earlier arrival of the heater induced quench. This results in the 'late' time signal, t_{feed}, being too early. A normal quench begins developing 10–15 msec before the trip threshold is exceeded; in the event discussed here, the quench did not begin until 10–20 msec after the trip. Since the arrival time plotted is the clock time, the uncorrected t_{return} is late relative to normal quench timing. These corrections to the pressure data move t_{feed} 10 to 20 msec later and t_{return} 15–25 msec earlier.[1] The corrected values place this event at essentially the same position as quenches #11 through #13; Fig. ____, an expanded view of the t_{feed} and t_{return} plot, illustrates these corrections.

Thus a turn-to-turn short developing at this position provides a very plausible explanation which unifies the interpretation of the data. The observation of the quench in power lead trip #5 would seem to strongly reinforce this explanation. From the strongly correlated position data, it is possible to conclude that these later quenches all occurred at the same location; the position of the short.

---

[1] The correction to the short time, t_{return}, is straightforward. The estimate of the correction to the longer time, t_{feed}, is somewhat less certain since it involves both the start of quench time (as in t_{return}) and the heater induced quench interference. For the cryogenic conditions of the test, the total magnet transit time is about 80 msec, so that t_{feed} can be estimated from t_{return} (after correction) and the calculated total time. The estimated uncertainties in the corrections are on the order of ±5 msec; the agreement with quenches #11–#13 is perhaps better than expected.

Operating Procedures

During a Test Run

The operating procedures for magnet testing has evolved from experience with previous magnets. Prior to each magnet excitation, the cryogenic conditions were checked for temperature stability, safety circuits were reset, and the magnet was ramped to a nominal 50 amp current before arming the Kautzky valves (pressure relief system) which are sensitive to noise during this initial phase. If no 'glitches' have occurred at this point, the final current value is set to about 7000 amps[1] and the ramp is resumed at a rate of 16 amps/sec. The ramp is interrupted by one of the safety circuit signals exceeding threshold and the quench detection procedure is initiated.

The quench detection procedure is designed to protect the magnet and cryogenic systems from the effects of the quench as well as to accumulate the monitoring data from the various sensors. Immediately following quench detection, the current power supply is commutated off. Signals are sent to the quench protection strip heaters and the pressure relief system valves. For most of the testing of magnet DD000Z, the strip heater signal was delayed about 135 msec and the Kautzky valve signal was delayed 250–300 msec.[2]

The computer systems then read out the digitized information from the various magnet sensors: coil, lead, and safety circuit voltages, currents, and $\frac{dI}{dt}$ from the electronic sensors; temperatures and pressures from the cryogenic sensors. These data are assembled in a data file uniquely associated by file name with the quench. The data are then processed to yield a quench summary containing the information characteristic of the quench: quench current, MIITs,[3] maximum voltages reached in the 1/4 coils, etc., as well as the date, time, and which safety circuit provided the trip. In addition, some rough consistency checks among the coil voltage signals are calculated: the 1/4 and 1/2 coil sums were required to

[1] The target current typically is set a few hundred amps above the expected short sample current for the operating temperature

[2] These delays are set to permit uncorrupted measurements used in quench position determination.

[3] MIITs $= \int_0^\infty I^2 dt \times 10^{-6}$; $t = 0$ corresponds to beginning of quench. In principle, knowledge of cable properties and MIITs determines maximum temperature reached by cable.

agree (within limits) with the total magnet voltage. If there is disagreement, a warning message was printed on the computer console.[1]

Following a Test

Following a quench, it typically took about two hours for the magnet and cryogenic system to return to stable conditions at the operating temperature.[2] During the interval between quench tests, the quench summary data as well as certain aspects of other data files were examined using both the online and offline computer facilities.

Two of the experimenter's primary concerns were the amount of cable heating due to the quench (the MIITs value) and the maximum voltages reached in the magnet. These values, available in the automatic quench summary, were checked following every quench. During DD000Z testing, no anomalies in these values were observed prior to quench #13.

The online and offline programs were then used to display and print out selected data channels: the 1/4 coil voltages, the voltage of the safety circuit responsible for the trip, the feed and return pressure transducers, and plots of resistance growth and I^2 versus time. These plots were reviewed to determine the origin of the quench (which 1/4 coil and an estimate of longitudinal position) and for quench development characteristics (rate of voltage/resistance growth, overall current decay time for MIITs studies, etc.). In the case of a power lead trip, the power lead voltage displays were examined to determine which lead (positive or negative) had caused the trip and if the voltage development was characteristic of quench development or was transient in nature.

The voltage plots were typically examined in the time region from about 50 msec before quench detection (nominal $t = 0$) to about 100 msec after detection. This time window did not include the region of peak voltage in the coils where

[1] Typically, the limit on disagreement was set at 5%. However, due to channel overflow and channel to channel discrepancies errors of 6–7% were not uncommon and were generally ignored. The disagreement was at the 25–30% level for quench #13 when the ground fault was detected by the safety circuit.

[2] Two hours is characteristic of operation at 4.3 K; recovery times of $\approx$ 3 hrs are typical of 3.3 K operation.

the first evidence of arcing or breakdown occurred, and thus the precursor signals of the developing problem were not discovered until a more detailed examination of the data was carried out later.

Safety Circuits: A Brief Description

The magnet tests are performed under computer control, during each test (magnet excitation), a number of electronic signals monitor the magnet and associated leads for quench development. These electronic signals are processed in 'safety circuits' which generate a 'quench' signal if a preset threshold is exceeded. If a 'quench' signal is generated, the current power supply is switched off, signals (with appropriate delays) are sent to the quench protection heaters and the pressure relief system ('Kautsky valves'), and computer readout of the test system electronic data is initiated. A description of the relevant safety circuits and their thresholds is given in the table below:

Channel	*Name*	*Threshold*	*Description*
SC#1	Upper-Lower Coil	.500 V	Upper-lower coil voltage difference primary quench detection signal
SC#2	Magnet-Idot	5.00 V	Magnet voltage minus $L\,\frac{dI}{dt}$
SC#3	Power Leads-Idot	.007 V	Power leads voltage minus $L\,\frac{dI}{dt}$ includes part of negative lead that runs length of magnet & back ('thru' & 'connected' busses)
SC#7	Ground Fault Monitor	2.5 A	Ground current monitor

Notes:

- The upper-lower voltage difference is the usual quench detection signal: the difference signal cancels the common inductive voltages and is sensitive to the resistive voltage from quench development occurring in one of the two coils (except in the case of a quench initiating simultaneously and symmetrically in both the upper and lower coils).
- The power leads are, for the most part, heavily stabilized and in low-field regions, thus the threshold must be set very low (7 mV) to detect very slowly propagating quenches.
- The ground fault monitor had been set to a high value (2.5 A) to avoid spurious trips due to noise from the magnet current power supply.

Tests Following the Failure

Following the failure of the beam pipe, and the identification of the ground short in the coils of the magnet, testing was secured, and the magnet was warmed to room temperature. Crews worked over the weekend and by Monday (11/9/87) all welds (except the beam pipe) were cut and the magnet was available for electrical measurements while still mounted on stand 4.

The results of the electrical measurements were recorded in the traveler and are summarized in the edited electronic mail message included at the end of this section.

The change in the lower inner coil resistance and the change in the trim coil resistances and their resistance to ground indicated that an arc between the inner coil and the beam pipe had occurred, with resultant damage.

This was confirmed a little later when DD000Z was moved to Stand 5 for convenience and a bore scope was used to examine the inside of the beam pipe. This is also described in the electronic mail message.

In addition to the data mentioned above, a visual inspection of all wiring was made. One of the expansion leads was found to be not well constrained by its holder as had been noted during installation.

On 11/12/87 the magnet was moved to the Industrial Center Building at FNAL and cryostat removal commenced. This proceeded routinely and the cold mass was readied for return to BNL.

During the initial meeting of this committee on 11/18/87 a request was made to measure the "bowing" of the end plates. This was done (see Fig. ____) and the "bowing" was found to be in rough agreement with strain gauge readings taken from these end plates prior to removal from the test stand, indicating a load on the plates presumably due to an increase in the relative length of the overall collared coil.

The cold mass was loaded for shipment to BNL on 11/21/87.

Inspection During Removal from Test Stand

Electronic Mail from J. Strait at FNAL Dated 11/12/87 (Edited)

I performed a number of measurements on DD000Z following warmup and the opening of the single phase region and before the magnet was de-wired and removed from the test stand. (The beam pipe bellows was still welded at the time.)

With approximately 1 A thru the main coil I measured the following voltages across the quarter coils:

Lower Inner	1.7945
Lower Outer	1.8431
Upper Outer	1.8452
Upper Inner	1.2831

The ratios of resistances among the last three coils match those from before the cooldown to better than 1 part in 1000, indicating that only the lower inner coil was damaged. (The ratios of coil resistances is much more accurate than the absolute values since the current was measured only with the small current meter on the power supply.) The voltages to ground from each of the 5 coil voltage taps was

Tap "A"	−5.5420
Tap "B"	−4.2588
Tap "C"	−2.4128
Tap "D"	−0.5689
Tap "E"	+1.2269

Taken at face value this puts the short to ground much farther from tap "D" than was measured inductively before the final quench.

All the 200 Ohms current limiting resistors on the five coil voltage taps, including the one through which the magnet was grounded on the last quench, were found to be intact, as were the 25 Ohm and 1 Ohm resistors in the external ground circuit that are used for ground current monitoring. It is pretty clear from this that very little energy was deposited in them compared with that which was deposited within the magnet.

The trim coil resistances were measured to be

Sextupole	1459 Ohms	(1491 Ohms)
Octupole	15.4 KOhms	(566 Ohms)
Decapole	918 Ohms	(948 Ohms)

where the numbers in parentheses are the values measured before cooldown. I was able to hipot the sextupole trim coil successfully to 800 V, but found the octupole coil to be 12 Ohms to ground from its negative lead and the decapole coil to be about 400 KOhms to ground, with the ground also very near its negative lead (measured by the floating DC power supply method).

The two strip heaters that were wired to the outside of the feed can (numbers 2 and 3) were successfully hipotted to 1000 V and 5 out of the 6 spot heaters were found to be isolated from ground with an Ohmmeter. Spot heater #3 (in the straight section near the non-lead end on the left side looking from the non-lead end) was 11.7 KOhms to ground.

After the magnet was removed from test stand 4 it was placed briefly on test stand 5 (onto which the turnaround box has not yet been mounted) to allow us to look at the damaged beam pipe with the bore scope, a 35 mm camera and directly. A video tape of the bore scope exploration was made. Based on this examination, the azimuths of the two holes in the beam pipe was estimated. The large hole was at about "6:30" o'clock and the smaller hole was at about "5:00". The "dimple" near the top was at about "1:00." The small hole was not round but was found to be significantly longer in the longitudinal direction. By using a stiff wire with a small hook on the end, I measured the distance from the face of the beam pipe flange to each of these three features. The large hole extends from 172 mm to 207 mm, the small hole from 202 mm to 219 mm, and the dimple was at 190 mm. (These measurements are estimated to be good to about ± 3 mm.) The dimple was about 2 mm high and about 6 mm wide at the base and there was a crack extending azimuthally across it and in both directions away from it for an estimated 10–30 degrees on either side.

Using the bore scope as a light source only and looking in directly, I could clearly see the severed ends of two cables which, by their position and angle, I would guess to be the two pole turns on the inner coil on the left side. The ends of the cables were quite "clean" and the individual strands were clearly visible. Unfortunately, I was unable to get a good picture of this with the bore scope due to the finite resolution of the fibre optics.

III. Inspection and Disassembly Sequence

(Not including measurements)

The cold mass arrived at BNL just before the Thanksgiving Holiday and was immediately removed from the trailer for its initial inspection. The first step was to remove as much equipment as possible from the interconnect regions, at the ends of the magnet, this included the two expansion loops in the leads between the magnet and power supply (Fig. ____). A careful examination of the area and of components as they were removed was carried out. During the inspection it was noticed that the plastic 'pultrusions' which act as carriers for the busses at the top of the yoke, and for the trim coil and other leads at the bottom, showed evidence of having extended out about one centimeter beyond their original positions at both ends of the magnet. The upper pultrusion was still extended, Figs. ____ & ____, the lower pultrusion had returned to it's original position. Each pultrusion is made up of three sections and it was later discovered that gaps had opened between the joints in the sections, which accounted for the increase in length (Fig. ____). The motion of the pultrusion ends had, in the case of the lower pultrusion, abraided the insulation of the trim coil leads (Fig. ____). The insulation of the main leads and buss at the upper pultrusion although showing pressure points was not damaged.

No new evidence was found to shed light on the 'lead events' that had been observed during testing. Following the disassembly of the interconnect region, four pairs of strain gauges were mounted on the skin of the cold mass, on the top at the return end. The gauges were located as shown on Fig. ____ and were oriented to read the longitudinal and azimuthal strain in the skin.

The bowing of the end plates that was indicated by the strain gauges mounted on the end plates and which had been confirmed by a direct measurement at FNAL was once again checked.

Dial indicators were clamped to the ends of the magnet so that the end plate deflection could be monitored during disassembly. The next step was to treppan the 20 fiducial mounts, in each case carefully examining the fiducial for any sign of motion between the yoke blocks and the skin of the magnet. This included checking the tack welds holding the fiducials to the yoke. Although not designed to do so, these tack welds would prevent relative motion between the skin and the yoke blocks at the location of the fiducials, the lack of damage at the welds indicating that no motion had occurred. At this time additional 'gauge holes' were bored through the skin to expose the surface of the yoke. These holes were at the feed end, in line with the upper fiducials, and spaced on 12-inch centers between the last fiducials and the end of the magnet (Fig. ____). These holes and the fiducial holes were sprayed with machinists blue and scribed such that relative longitudinal motion between the skin and the yoke during the disassembly could be monitored (Fig. ____).

The cold mass was then rotated 90 deg. ccw. viewed from the lead end, guide rails were attached, and a hand-held electric saw with an abrasive cut-off blade was used to cut through the top of the skin longitudinally, a few degrees above what is normally the magnet mid plane. The cutting speed was 1 meter per hour. The cut started at the center and was carried 6 meters towards the return end, then reversed and carried from the center completely through the feed end (Fig. ____) including the bonnet. [The bonnets are machined stainless steel cylinders about 6 inches long that form the ends of the cold mass. The end plates are constrained from moving outwards by retainers that fit in grooves machined in the I.D. of the bonnets. The bonnets are welded to the stainless steel skins (Fig. ____).] The return end cut was then completed, continuing through the return end bonnet.

The skin of the cold mass was then clamped circumferentially, it was rolled 180 degrees and a second cut was made starting at the return end bonnet and continuing the entire length of the magnet. Again the cut was at a location corresponding to a few degrees above the mid-plane.

Following cutting, the magnet was rolled back to its normal orientation and the clamps were removed. At this point the load on the lower half end plates had increased significantly. The load on the top half of the end plates had reduced to near zero and it should have been possible to remove the upper half of the skin. However on attempting to remove the skin it was found that the circumferential weld attaching the bonnet to the skin had penetrated sufficiently to fuse the skin to the yoke, since no welding back-up plate is provided at this location. At the return end of the magnet it was possible to break this bond by prying the skin from the yoke. At the feed end, a half circumferential cut was made adjacent to the weld, and the top half of the skin and the top half of the return end bonnet were removed. The upper pultrusion was then exposed but was still locked in place by the top of the feed end bonnet.

Longitudinal cuts were made in the bonnet on each side of the pultrusion and a small piece of the bonnet and then the pultrusion were removed. The small piece of the bonnet included a section of the circumferential weld between the bonnet and the skin. This piece was sent to the metallurgical laboratory at BNL for examination of the weld (Fig. ____).

The top half yoke blocks were now visible. Each block is approximately 6 inches long, with nominal gaps between blocks of .105 inches (Fig. ____). In this case the gaps were found to vary widely along the length of the magnet. The gaps were measured and recorded before proceeding with the removal of the upper half blocks.

The blocks were removed one at a time starting at the center and proceeding towards the return end, and then from the center to the feed end, carefully monitoring the instrumentation. The blocks were all easy to remove, the only load on them apparently being their own weight. The top half of the feed end bonnet was removed with the last yoke block. At this point the load that had been carried by a full end plate at each end had now been completely transferred to a single half end plate at each end with a corresponding increase in deflection.

It was not known if the load on the end plate was being exerted by the entire length of the collared coil acting as a long spring, or if the coil was 'locked' some distance from the ends, with only the end section loading the end plate and the rest of the coil being relaxed. To enable the two ends to be examined separately, a single yoke block was replaced about 2 meters from the feed end and held in place by a clamp applied around the outside of the block and the skin (Fig. ____).

Starting at the center and proceeding towards the return end, the collared coil was then gently pried-up from the lower yoke using a small lifting tool. This process was very easy to carry out, little force was required to move the collared coil. Small spacers were put under the tabs on the collars in several places to hold the assembly a few millimeters above the yoke. This procedure continued until a section of the collared coil extending from the center to about 1/2 meter from the return end was raised in this way. There was no significant change in the load observed at either end plate.

The next step involved passing lifting slings around the collared coil, about 1 meter each side of its center, and using these slings to lift the assembly a few inches above the yoke. Again the load on the end plates remained unchanged as the coil was raised until it had been lifted approximately 6 inches above its normal position. Then the load on both end plates reduced to zero simultaneously. The end plate retainers at the return end were then removed and the coil was lowered to its original position. As the coil was lowered it pushed the return end plate outwards approximately 0.2 inches while remaining in contact with the end plate at the feed end. The retainers and end plate at the feed end were then removed, the single remaining yoke block unclamped and the collared coil assembly lifted up using the normal lifting fixture.

Using a micrometer, the outside diameter of the collars was measured in several locations, repeating measurements taken following the initial collaring and recorded in the traveler. The collared coil assembly was then positioned on the collaring press. Dial indicators arranged to monitor longitudinal motion at both ends of the coil, and uncollaring commenced at the return end and proceeded as far as the middle of the coil. When the collar packs had been removed from half of the coil, the exposed upper coils were lifted at the end to reveal the beam pipe and the damaged area, in the 'fish-mouth' see Fig. ____. Following an initial inspection the beam pipe was also raised, inspected further, and then severed using a hack-saw, about half a meter inside the damaged area.

The damaged section of the lower inner coil was then lifted out of the lower outer coil and cut off at the same location. The damaged section of the lower inner coil, the piece of the beam pipe, the collars, and the surrounding insulation were then removed to a different location for a detailed examination later (Fig. ____).

The remaining section of the lower inner coil was still in place still collared over half its length. It was now possible to measure the dielectric strength of the insulation surrounding the individual conductor sections. Using a Hipot, the dielectric strength was measured between conductors and wedges, between each conductor and the collars, beam pipe and outer coil, and also across the mid-plane turns. Turns 1, 2, and 3 between the pole and the first wedge were found to have tens of kilohms resistance turn to turn and this resistance was monitored during the subsequent uncollaring. The uncollaring process recommenced at the center of the coil and continued towards the feed end.

Coils are normally collared by compressing 5 packs at a time, 5 six-inch long packs corresponding to the length of a 30-inch long key. Uncollaring was a reverse of this procedure. However, due to the repair that had been effected at the feed end of the coil after the final assembly, the last 8 collar packs had been collared and keyed individually using 6 inch long keys. In this case, the packs were removed such that alternate packs were left in place on the coil. Then, using a vernier-caliper and feeler gauges as illustrated in Fig. ____ the length and 'tilt' of the top of these remaining packs was measured. Following this measurement, the remaining packs were removed and the upper coils completely exposed. The upper coils were then removed and examined and the beam pipe separated from the lower coils.

Since the collars are laminations, the inner surface of the collar packs is not a smooth surface. To avoid having the coil insulation in contact with this surface, strips of stainless steel called 'Venetian Blinds' were interposed between the coil and the collars. When the venetian blinds were removed, in addition to the normal, faint, azimuthal imprint from the collars, there was also an axial ridge at the magnet midplane. This ridge was a rounded, inward indentation of about a millimeter and was evident to varying degrees on most of the venetian blinds.

The final step in the disassembly sequence involved a close examination of the feed end beam pipe in the region of the coil end where an internal crimp had been detected at FNAL. An inspection of the insulation on the pipe revealed a series of dimples where it had been in contact with the voltage tap wire (Figs. ____ & ____). The trim coils and insulation were removed layer by layer and measured until the bare beam pipe was exposed and it too could be measured.

IV. Observations of Mechanical Features During Disassembly of the Cold Mass

Skin

The principal observation was that the top half of the skin grew relatively smaller azimuthally and longer axially when it was cut away from the bottom half. The azimuthal behavior is consistent with that expected due to welding stresses, the axial behavior following from the Poisson effect.

The decrease in the azimuthal size of the upper half skin was seen in the gap between halves after the first longitudinal cut. The gap was about twice as large as the 1/8" kerf of the grinding wheel, even though the skin was clamped to the yoke. It was also seen in the motion of the skin with respect to the yoke blocks, observed through the fiducial and 1"-diameter gauge holes drilled through the skin. (In principle, the motion could be determined from the position of the hole with respect to the blueing sprayed on the yoke through the hole before the skin was cut. In practice, this turned out to be difficult to do with precision.)

The increase in the length of the top half skin was measured by comparing it to the bottom half skin after both longitudinal cuts had been made. The top half was 0.1" longer, with the added length appearing equally at both ends (Fig. ____). The bottom half, which encompassed somewhat more than 180 degrees and included both backing strips, was locked to the lower half of the yoke and had not yet released the hoop tension due to welding at the time this measurement was made (Fig. ____).

To monitor the strain in the skin, four pairs of strain gauges had been installed at the top of the exterior of the skin. Each pair had an axial and an azimuthal gauge. Pairs were installed at 3-foot intervals starting at the nonlead end of the skin. The gauges were zeroed after the initial cut in the skin had been made from the magnet center to just past the nearest pair. After both cuts had been made, the gauge readings qualitatively agreed with the skin motion described above. However it should be pointed out that the skin of the magnet was expected to have very high residual stress levels due both the forming process and to its history of welding and cutting. Strain gauge readings should be viewed accordingly.

The azimuthal gauges on the skin decreased an average of 70 microstrain after both cuts were completed, indicating that the hoop stress in the top of the skin before cutting had been 2 kpsi. Experience with welding the skins together suggests that after welding, the material near the midplane is near yield (30 kpsi). These numbers can be reconciled if there was significant friction between the skin and the yoke, as appears to have been the case (see below).

A typical axial gauge on the skin increased approximately 260 microstrain after both cuts were completed, indicating a longitudinal stress of 7.7 kpsi in the skin before cutting.

This measured value occurred at a location at the top of the skin where the azimuthal stress had been found to be very low; however if one assumes an average azimuthal stress in the skin of 20 KSI then the expected average axial stress from the Poisson ratio would be of the order 7 KSI. This would cause an elongation of the half length of the skin of .090", rather than the observed .050". However the observed change of .05" was a measurement of the length of the top half of the skin relative to the bottom half. Although the bottom half was locked to the yoke and was observed to still have some hoop stress after the cut, there was no way to ascertain the magnitude of this stress. A loss of approximately half the hoop stress in the lower skin could easily account for this discrepancy.

Before cutting, the skin was subjected to an axial tensile load of approximately 7 K-lbs as indicated by the outward bowing of the end plates. The estimated extension of the skin due to this load is of the order .012" over the half length. The contraction of the skin by this amount following cutting was offset by the much larger Poisson effect described above.

A typical history of the strain gauges is given in Figs. ____. Aside from the starting and ending values discussed above, the most prominent features are the changes caused by the first cut passing through the axial position of the gauges, by the two rotations of the magnet, and by the second cut. Many of these changes indicate complex behavior, which is not surprising in view of the stress history of the skin and the effect of supporting the weight of the cold mass on five azimuthal rollers. Also, the gauge pair closest to the return end may have been affected by local distortions from the welding of the skin to the bonnet.

half than the bottom half, although this conclusion has an uncertainty because the gaps were not necessarily parallel and a single approximate measurement was recorded for each gap.

Analysis of the skin-bonnet weld indicated a lack of fusion in the area examined, illustrating the need for a weld prep as provided in the current design.

End Plates

The small space between the ends of the coils and the end plates was filled with green putty approximately 1/4" thick, and there was an annular space approximately 3/4" long between the ends of the yoke and the end plates. The end plates were flat when they were installed in the magnet, after the welding of the skin, and were found to be flat within a few mils following disassembly.

After the test of the magnet, the end plates were bowed out an average of 0.010" to 0.012", the measurements of the bow at Fermilab and at BNL (Fig. ____) agreeing with one another within a few mils.[1] Within 0.002", the bow was the same at both ends of the magnet. We conclude from this, only that the transportation by road, of the cold mass from FNAL to BNL did not measurably affect its state of strain.

During the initial assembly of the magnet, orthogonal strain gauge pairs with strain free compensating gauges had been mounted on both half end plates at the return end and on the top half end plate at the load end of the magnet. These gauges were monitored during tests at FNAL, the FNAL measurements having been recorded with the strain gauges connected in a full bridge circuit. At BNL, during disassembly, readings were taken from individual strain gauges, the change in one of these gauges, during the disassembly sequence is shown in Fig. ____. The variation of the strain during the disassembly sequence indicates very large changes associated with rolling the magnet over during cutting, and this, coupled with the errors arising when attempting to correlate the two sets of data from the different methods of reading the gauges, has precluded a more detailed quantitative analysis of these results.

[1] Except for one Fermilab measurement of a bow of 0.028". Given the difficulty of taking the data in a region generally full of interconnect hardware, the agreement is excellent.

Skin Yoke Interface

A prominent feature of this system is the close contact between the yoke and skin, the location and spacing of the yoke blocks being controlled only by the friction resulting from the clamping force applied to them as the skin is welded along its length.

Evidence of the contact force between the yoke and skin appeared as shiny lines on the inner surface of the skin. Lines appeared near the pole, where the yoke is recessed to allow for the buss pultrusion (Fig. ____). Several other lines, parallel and with 1-1/2" spacing, also appeared. The 1-1/2" spacing corresponds to the space between successive "bumps" of the skin in the process of making the semicircular skin from a flat plate. Shiny areas corresponding to the shiny lines were also evident on the yoke blocks. It was not possible to tell from visual inspection of the shiny lines whether the yoke blocks had moved axially.

However an electromicroscopic examination of the marks ......

The yoke blocks that carry the fiducial plugs are attached to the skin by the small tack welds that hold the fiducial plugs to the yokes. (The outside collars of the fiducial plugs are then welded to the skin). The tack welds at the 20 locations were examined and found to be undamaged when the fiducials were cut out (treppaned), indicating that these yoke blocks had not moved from their initial positions.

An examination of the yoke blocks revealed that the largest gap between blocks was 7/16" (0.43"), as compared to the nominal spacing of 0.105". The gap occurred in the lower half yoke, between the center fiducial block and the next block toward the return end.[1] The other gaps are not evenly distributed. There are significantly more large gaps in the return half of the magnet than in the lead half, for both top and bottom yokes (and a corresponding number of gaps reduced to near zero). It also appears that there were more large gaps in the top

[1] The technicians who had assembled the magnet, state unequivocally that the magnet would never have been assembled with such a gap, although typically the gaps have been seen to vary up to 0.2".

For an understanding of the observations recorded during the disassembly of the magnet we can assume that the total load applied to the end plates at the time of disassembly was 7000 lbs.

Before the disassembly this load was divided equally between the two halves of the end plate at each end, and was observed to transfer to the lower half end plate alone, with a corresponding increase in strain and deflection, when the top half of the skin was removed.

The axial motion of the magnet, the loads applied to the end plate during operation, and the elastic constant of the end plate are under detailed study at BNL and CDG.

A final indication of the magnitude of the load on the lower half end plates when the full load was transferred to them, was the observation that the retaining clips holding the end plates to the bonnet had yielded and were noticeably bent outwards.

Yoke Collar Interface

Collars are pinned together in packs about 6" long, with the pins extending slightly beyond the collars. When the collar packs are installed on the coils, the pins from adjacent packs abut, giving uniform spacing of the packs. The spacing between adjacent packs is also held by the keys, which are 30" long and installed in overlapping fashion along the magnet. No variations in collar pack spacing were noted when the top half yoke was removed and a visual inspection performed.

The yoke had shiny spots where it had interfaced with the collar, however, these contact areas were not larger toward the end of the magnet than at the center, as might be expected if the collared coil had moved in the yoke when the magnet was excited. Nonetheless, this type of motion cannot be excluded. Also, the collared coil rose freely from the yoke when it was lifted, indicating that the collars were not wedged into the yoke.

A further significant observation was that although a single yoke pack had been clamped in position near the feed end, before the coil was raised, the load on both end plates reduced simultaneously. This would indicate that the single yoke block had been ineffective as a clamp and had not restrained the longitudinal motion of the collared coil within the yoke.

Collared Coil

Two most interesting observations were that the collared coil lengthened by approximately .2" when it was released during the disassembly, and that as the collar packs were removed the length of the coil assembly decreased linearly with the number of collar packs removed for a total reduction of .135" (Fig. ____).[1] Also, for several collar packs which were individually keyed at the lead end, the collars had become spread out by about 0.03" at the collar inner radius, in the pole region of the magnet (Fig. ____). It is not known if this effect was an artifact introduced by the non-standard collaring procedure, or if this effect can be expected normally.

The azimuthal prestress on the coils following final assembly was 8 KSI for the inner coils and 6.3 KSI for the outer coils. One of the two inner coil strain gauges had changed by only 4 microstrain from the last reading taken at BNL before the test, 284 microstrain. The second inner coil gauge was inoperative. Three of the outer coil gauges had changed only 0, 7, and 20 microstrain from their pre-test values of 200–300 microstrain, the fourth being inoperative. The outer diameter of the collared coil was the same before and after the test, within the accuracy of the measurement, about 2 mils.

Coil Insulation

At the pole, the coils are insulated from the collars with a folded piece of kapton called the "Z-cap" (Fig. ____). Except in the region of the ground fault (see below) the Z-cap was found to be correctly positioned and a visual inspection

[1] For reference, the coils for magnet DD0010 were collared immediately following the disassembly of Z and the change in length of the coils due to the collaring was measured as being +0.25". We assume that this is equivalent to the Poisson effect, however since the constitutive properties of the coil have been characterized as being (non-linear) orthotropic thermo-visco-elastic-plastic and non-thermal realogically simple, verification of this assumption must be sought elsewhere.

revealed no damage. The green putty end saddles which were used to square-off the rounded coil ends were still attached to the coils and the green putty which fills the gap between the end saddle and the end plates was not cracked.

In testing electrical insulation, the focus was on measurements which could not be performed on assembled magnets, such as the insulation between upper and lower coils and turn-to-turn insulation. With the damaged section of the lower inner coil cut away and half the length still collared, the remainder of the coil was hipotted successfully to the remaining three coils and ground at 3 kV. The integrity of the turn-to-turn insulation was inspected by hipotting each turn to its neighbors and ground at 1 kV. The 13 turns in the three blocks starting from the midplane drew no current at this voltage. The insulation between two pairs of these turns was tested to failure, breakdown of the turn-to-turn insulation occuring at 1.7 kV and at 2 kV. The maximum turn-to-turn voltage expected for a worst-case quench is thought to be in the vicinity of 600 V. The three turns in the block nearest the pole had turn-to-turn resistances of a few times 10 kohms, but drew no current to ground at 1 kV. These turn-to-turn resistances were monitored as the remainder of the coil was uncollared. One value remained in the 30 kΩ range, another immediately increased to 20 MΩ as the last collar pack was removed and the third slowly increased to 20 MΩ during several minutes following uncollaring.

Following disassembly and with the aid of tooling which applied pressure to a 6" section of one quadrant, the contact region was found to be in the last 6" of the straight section, in the quadrant which did not contain the splice between inner and outer coils. (Tooling to compress the end region of the coil was not available.)

Trim Coil Interface to Main Coil and Collars

The bumpers which position the trim coil radially by pressing against the main coil were found to be rotationally out of position in some instances, so that they rested against the poles of the collars instead of against the first block of the coils. There was no evident damage, however.

The keys which are responsible for the angular alignmnent of the trim coil were correctly positioned in the collars.

Interface Between Beam Pipe, Trim Coils and Main Coils

After the magnet was disassembled, measurements of the radial thickness of the lower inner and outer coils were made at the lead and return ends at several axial and azimuthal locations. Vertical and horizontal coil radial thickness readings were averaged for the tabulation below. The diameter of the lead end beam pipe, before and after removing the insulation, was also determined at a number of locations and these measurements are shown in Figure ____. The beam pipe was not measured at the return end because its insulation was badly charred and distorted. For comparison purposes, it was assumed that the diameter of the return end beam pipe plus insulation was identical to the lead end average diameter. The following tabulation (all readings in inches) was used to estimate the radial clearance between the beam pipe and the inside of the inner coil:

Item	Lead End		Return End		Nominal
	Vert.	Horiz.	Vert.	Horiz.	
Collar inner radius	1.613	1.613	1.613	1.613	1.613
Venetian blind	-0.015	-0.015	-0.015	-0.015	0.015
Kapton	-0.005	-0.005	-0.005	-0.005	0.005
Kapton	-0.005	-0.005	-0.005	-0.005	0.005
Heater + insulation	-0.010	-0.010	-0.010	-0.010	0.010
Kapton	-0.0035	-0.0035	-0.0035	-0.0035	0.0035
Kapton	-0.0035	-0.0035	-0.0035	-0.0035	0.0035
Outer coil thickness	-0.406	-0.404	-0.415	-0.406	0.396
Coil caps (4 × .004)	-0.016	-0.016	-0.016	-0.016	0.016
Teflon	-0.002	-0.002	-0.002	-0.002	0.002
Inner coil thickness	-0.416	-0.401	-0.435	-0.405	0.379
Coil inner radius	0.731	0.748	0.703	0.742	0.778
Beam pipe + insul. (Avg)	-0.720	-0.720	-0.720	-0.720	0.723
Radial clearance (interference)	0.011	0.028	(0.017)	0.022	0.055

The lead wires to the mid-plane spot heaters exit to the outside world along the horizontal axis on both sides of the beam pipe. These wires measured 50 mils in diameter over the wire insulation, and therefore, must have been pinched between the beam pipe and the inside surface of the coil package. Similarly, the two inner-to-outer coil splice voltage tap leads exit along the vertical axis on both the top and bottom of the beam pipe (Fig. ____). These wires measured 75 mils new and 45 mils "squashed," therefore, these leads also must have been pinched between the beam pipe and inner coils.

The annulus between the outside of the beam pipe assembly (including trim coils) and the inside of the main coils, forms an important passage for the flow of liquid helium. The impact on the cryogenic design of obstructing this passage has not been considered in this report.

Buss Work and Expansion Joint

A puzzle during the magnet test was a voltage which developed across the expansion joint and through-buss of the magnet, discussed in a previous section. This part of the buss work was inspected carefully to try to find the cause of the problem. Two obvious departures from design were found.

The first was that the bottom of the negative lead expansion loop of the buss did not lie in its G-10 track. This was noted at Fermilab both before and after the magnet test. At BNL, the bottom of the expansion loop is tied to the G-10 track as a shipping restraint and is untied on receipt at FNAL.

Fermilab techs also reported difficulty slipping the bellows over the interconnect region prior to welding (Ref.: Inspection at Fermilab section). At BNL, a bellows is slid over the interconnect area as part of the outgoing inspection procedure.

In this magnet the yoke laminations at the ends of the magnet were replaced with laminations of nonmagnetic stainless steel, and the stray magnetic field strength in the region of the expansion loops is not well known. Without precise calculations of the field strength supported by measurement of the actual field it has not been possible to establish conclusively whether or not irregular motions of the expansion loop could generate the signal necessary to trip the quench detection circuit.

The second problem was the position of the pultrusion which carries the buss. (It does not provide electrical insulation for the buss.) The main buss pultrusion was extended about 3/8" beyond its normal position, at both ends of the magnet. The pultrusion is made of three separate, glued-together pieces. If the thermal contraction of the pultrusion is close to that of uniaxial G-10, it will contract significantly less than the cold mass. When the system is warmed up, friction could restrain the pultrusion and break the glue joints. Glue joints were found to be broken at the expected places. Although the trim buss pultrusion was found to be in the correct position, the kapton insulation of the buss wiring was torn in the way expected if this pultrusion had moved beyond the end plate and then back into the correct position. These observations were in agreement with the model of differential thermal contraction. Problems which might have produced the nonresistive lead voltages were not found.

Arc Damage

The damaged area in the lower inner coil was most severe at the end of the coil straight section, in the block of three turns closest to the magnet pole. Missing sections from these turns extended about 1" into the straight section and an equal distance into the end In addition, the beam pipe located just below this region had melted away in several places over 1"–2" region axially, and 20–30 degrees azimuthally, as noted in the inspection at Fermilab (Fig. ____).

The arc had also severed the octupole trim coil, which is located in this region, and the leads to the decapole trim, which pass through the region. The last collar in the straight section (i.e., the last collar to have a pole piece) had suffered significant melting of the pole and the five collar laminations adjacent to it had suffered varying degrees of damage in the pole area (Fig. ____). A 1/2" portion of the 5-mil kapton "Z-cap" which presses agains the pole shim and insulates the coil from the collars was burned away in the same area. In this magnet the Z-cap ended at the end of the straight section, where the collars with pole pieces stop and the collar packs which constrain the coil ends begin. This is just at the point of discontinuity where the insulation was overstressed due to the wedge tip problems described in Section I. Normally the Z-cap would extend somewhat further into the end region of the coil, overlapping the G-11 pole spacer by about half a centimeter.

The damage was sufficiently extensive that an inspection did not shed light on the question of whether the initial problem was a turn-to-turn insulation failure or a coil-to-collar insulation failure.

Away from the immediate vicinity of the damage, the portion of the Z-cap which lies between the beam pipe and the inner coil was missing (presumably melted) for about 6". For up to 2 feet away, the same portion was out of position (Fig. ____). To some extent the cap was curled but it was also creased incorrectly. There are two possibilities: that the Z-cap was assembled incorrectly, or, it appears much more likely that the Z-cap was softened and then moved out of position by the passage of the hot helium at the time of the ground fault. In no other area was the Z-cap found to be out of position.

No damage was evident in the other three windings, aside from some blackening of the upper inner coil. (Analysis of the black material yielded Si, Ca, Ti, Cu, Nb, and Al.) The trail of blackening indicated that the helium had flowed several feet toward the lead end, and also into the return end. The flow toward the lead end (i.e., into the straight section of the magnet) was much greater than the other direction, insofar as could be judged from the carbon trail. Molten metal from the arc had splatten the yoke blocks at the axial position of the ground fault.

V. Documentation

The fabrication and assembly of SSC long magnets is monitored and recorded from the initial superconducting wire and component production through to final preparation for testing. The original data is normally compiled into a document called a 'Traveler' which remains with the magnet, the amount of data increasing as the magnet components move from place to place during the fabrication process.

In the case of magnet Z, the traveler was in two sections, the first section originating at BNL during the cold mass assembly, the second section originating at FNAL during installation of the cold mass into the cryostat and preparation for testing.

Detailed records of the superconducting material, the filaments and the wire, although available from LBL, did not form a part of the traveler, which starts with the mechanical and electrical testing of the superconducting cable at BNL.

The traveler was examined in the context of determining whether any information could be found that would point to impending problems, and to formulate general comments about the traveler itself and possible improvements to its contents and format.

It was found that the electrical measurements reported in the traveler were complete and quite consistent. The concept of performing the electrical measurements on a regular basis is important because problems can be discovered in a timely fashion. It should be noted that consistency can be improved if the ratio of resistances is compared rather than their raw values. This tends to eliminate the effects of changes in measuring current and temperature variations.[1]

The final short discovered on 8-11-87 was particularly perplexing, since the short was detected 5 days after the welding was completed. The records show that this was a repeat of an earlier short, and rather than just inserting additional insulation into the area, the pole spacer was trimmed to remove the step between the pole spacer and the pole shim as described in Section ____. The step, and the

[1] At room temperature the electrical resistance of copper increases .4% per degree C, so care must be taken to yield accurate measurements.

overpressure on the insulation were not corrected on the other end of the magnet where the fault eventually occurred. The subsequent resistance measurements performed at BNL and FNAL, which were in quite good agreement with each other, gave no indication of a short or ground fault.

Prior to shipment, warm magnetic measurements were carried out at BNL. There is no record in the BNL section of the traveler of any difficulty in performing these measurements and no record of any beam pipe abnormalities.

Similar measurements were carried out at FNAL using a somewhat larger measuring probe, and in this case, serious crimping of the beam pipe was detected at both ends of the magnet and recorded in the FNAL section of the traveler. The diameter of the beam pipe is now checked at BNL with a pull-through gauge, so this condition will not go undetected in the future.

The cable widths for both inner and outer cable listed in the traveler for DD000Z are 3.6 mils larger than design, whereas a value equal to the design value was measured at LBL during the cable manufacture and reported in their data sheets. Any differences between LBL and BNL measurements must be understood and noted in the traveler, and approval to proceed must be given by a responsible person.

At the BNL-FNAL interface the BNL turnaround documents are ignored and FNAL issues their own. In the case of the electrical measurements, there was close agreement between the BNL and FNAL measurements. The accelerometer data obtained during the shipment of the cold mass was not recorded in the traveler.

In general, both travelers contained a great deal of vital information, however, there were serious deficiencies in both documents. Proposals for improving the usefulness of the traveler can be found in Section ____.

VI. Related Incidents With Other Magnets

For completeness, in this section we delineate insulation failures that have occurred in other similar magnets.

The first long magnet in the SSC program D0001 suffered turn-to-turn insulation damage during curing, the damage was attributed to a mislocated liner in the curing press. A repair was effected by inserting layers of kapton between turns in the damaged area. Subsequently, a coil to ground leakage path was discovered during hypot testing following assembly. This fault was found to be due to a metal chip from a collar pack pin.

During testing at FNAL this magnet developed a resistive short to ground. The location of the short was estimated, the system ground moved to the nearest voltage tap and the test program was completed. When the magnet was warmed up the short to ground disappeared.

On D0002 an insulation repair was made when during assembly, a short developed in the end region of an inner coil. No problems developed during testing. 7 assemblies (shorts!)

D000X, a heavily instrumented magnet and the precursor to D000Z was suspected of having a turn-to-turn short during collaring. During examination, no specific reason for the short was found and there was some evidence of instrumentation error. The magnet operated successfully and is still in use at FNAL.

SLN012, an early 1.8 m long, very heavily instrumentation magnet was equipped with multiple, voltage taps and heaters to assess quench margins and to make propagation velocity studies. The magnet was tested successfully and eventually foiled while being operated at a field of nearly 8 T. The failure was attributed to a turn-to-turn short in the inner coil.

During the ongoing BNL program of constructing and testing 1.8 m long magnets, several problems have developed during the course of fabrication and assembly but, following corrections, have never manifested themselves during testing. For example, DSS001 and 002 were insulated with 55–45% triple overlap like D000Z and had the excessive buildup on the wedge tips. This problem was initially identified on these short magnets but did not result in failures during operation. On magnets DSS004, 005, 006 and 007 the insulation scheme was changed to the current 45% double overlap used on long mgnets after D000Z. As the new C358A design was debugged several turn-to-turn and high pot failures occurred on the early magnets, however the problems were eventually corrected and on magnet DSS006 no probems have occurred during several assemblies and the magnet has performed flawlessly (one training quench).

Magnet DSS009 was also a 1.8 m magnet built under a collaborative agreement between LBL and BNL. The magnet was the precursor to DD0011 and DD0013 long magnets with aluminum tapered key collars. During assembly a turn-to-turn short occurred on the inner coil this was corrected, and during testing the magnet operated in a manner similar to DSS006, reaching full field with only one training quench.

Magnet D15A2M1 was a 1-meter LBL magnet similar in design to DSS009. It was subjected to series of tests and modifications. After 3000 ramp cycles it failed in a manner similar to D000Z. It did not have a beam pipe but the failure occurred at the discontinuity between the straight section and the end region. It resulted in damage to the pole area of the inner coil and the last few collars. A report of the investigation of the failure is listed in the bibliography.

VII. Salvage of Components

Following the disassembly of magnet DD000Z many of the component parts were assigned for reuse in other magnets.

The entire cryostat assembly at Fermilab will be used for a subsequent magnet (probably DD0012). This includes the vacuum tank, heat shields, supports, superinsulation and all of the bellows.

Some parts of the cold mass were unfit for further use. Principally the skin which had been cut and welded many times; the bonnets, which had been cut through during disassembly; the inner coils and beam pipe; some of the yoke blocks which had been fused to the skin, the ground plane insulation; and the collars from the damaged area.

Approximately 1000 of the 1100 collar pairs were reused on magnet DD0012, enabling it to stay on schedule. This magnet was expected to be delayed when it was found that the collars assigned to it were out of tolerance due to wear on the suppliers die plate.[1] An attempt was made to correct the die-plate by restoring it, but this effort was unsuccessful, and a new die plate was manufactured. The use of the collars from DD000Z supplemented by others from Laboratory stock, averted a considerable delay in the program.

The outer coils from DD000Z were examined and tested and found to be undamaged. It is planned to reuse these coils on magnet DD0015.

The committee feels that there are risks associated with reusing these coils but it is beyond the scope of the committee's charge to comment further on this matter.

The iron yoke was reused in DD0012 along with many of the miscellaneous electrical end parts in the interconnect area.

[1] Due to the toughness of the Nitronic 40 collar material.

VIII. Findings and Recommendations of the Committee

1) *Tests of Magnet DD000Z Have Contributed Significantly to the Program*

Magnets DD000X and DD000Z are the first two of the long, straight-ended magnets. The tests of Z have contributed significantly to the body of knowledge about this type of magnet. In quench behavior, Z was a slight improvement over its precursor X and the data from these two magnets now represents a datum against which future magnets can be compared.

The special instrumentation used on Z gave unique results which, combined with the information derived from its disassembly, has contributed more to our knowledge of the engineering behavior of these magnets than any other previous magnet. Some features of this magnet could not have been studied other than by disassembling a magnet following operation.

2) *New Features*

Many new design features that previously had only been tested on short magnets were incorporated into the design of DD000Z, there were:

- C358A Coil Cross Section
- Spot Welded Collars
- Filled Ends
- NC Machined G-11 Pole Spacers
- 12' Long Copper Plated Section Inside Beam Pipe
- Smaller Yoke Cut Outs for Improved Field Uniformity
- Space for Warm-up Heaters in Yoke
- 1.55:1 Copper-to-Superconductor Ratio (Inner Coil)
- Straight Ends Designed with Spacers for Neutral Harmonics
- St. Stl. Yoke at Ends (2.4" into Straight Section)
- New Trim Coils b_2, b_3, b_4

- Yoke Blocks Held by Flared Tubes
- The Length of Z was Extended to Accomodate Extensometer Ring

Also R&D Instrumentation

- Azimuthal Coil Prestress
- Strain Gauges on End Plates
- 5 Voltage Taps
- Cold Pressure Tap at Center (Piezo-Electric)
- Thermistors on Both End Plates

3) *Insulation Failure*

The destruction of the lower inner coil of magnet DD000Z was caused by a failure of the electrical insulation of the coil, the weakness in the insulation system being precipitated by several flaws in the construction of the magnet. Many of these flaws had been identified and corrected on later magnets even before this magnet was disassembled.

It seems probable that turn-to-turn insulation failure occurred either before or simultaneously with one or multiple ground faults.

The insulation failure was first in evidence at quench #10 and the magnet deterioriated steadily as the voltage in the coils increased with the subsequent quenches.

The final quench, #14, occurred at an anomolously low current, indicating that significant damage to the magnet had already occurred.

The ground current ($\sim$ 10 A) during the previous quench is not compatible with ground current being the only abnormality and the ground current observed in the system ground during the final quench, by itself, could not have provided sufficient energy to rupture the beam pipe. Also in the final quench, no significant ground current developed until 300 ms after $t = 0$.

The behavior observed in the power lead trip following quench #12 is strongly supportive of the assumption of a turn-to-turn short. Resistive voltage developed in the lower inner coil after the trip but earlier than the outer coils which are in contact with the quench heaters. The large $\frac{dI}{dt}$ that follows power supply turn off could have driven current in the shorted turn(s), inducing a quench in the lower inner coil.

Although the early indications of unusual behavior starting with quench #10 were not immediately recognized during testing, operational procedures for magnet testing are not implicated in the failure of the magnet.

4) *Deficiencies in Magnet Construction*

A) The committee concluded that the following features which affected the region at the end of the straight section had a direct bearing on the failure:

- Material build-up at wedge tips
- Mismatch of pole spacer and shim
- Z cap did not overlap pole spacer

In addition the coils were slightly oversize in azimuthal dimension and the compliance of the ends was reduced by the filling process, both of these features may have contributed to the problem. In the following paragraphs we describe these deficiencies in more detail.

i) Wedge tips. The transitions between the wedges and the wedge tips had, in earlier magnets, been identified as a potential source of trouble. The addition of insulation was a solution that had proved effective in these other magnets.

In magnet Z there were several reasons why this solution was no longer appropriate:

- The number of wedges in the inner coil had increased from 2 to 3.
- To optimize the magnetic field properties, care had been taken to make a clean transition from the straight-section to the end of the coil. This exacerbated the buildup by bringing all the wedge tips to the same axial location.
- The design of the new straight end was less tolerant of perturbations than previous end designs had been.

The new C358A cross-section with straight ends was tested on short magnets in May 1987 and these deficiencies were discovered, however the fabrication of the coils used in Z preceeded this date, having been wound in March. Since it was no longer possible to change the wedge-tip insulation, adjustments were made instead in the pole shim.

ii) Step between pole space and shim. The coils of magnet Z were slightly oversize in the azimuthal direction following curing. For this reason, and the reason relating to the wedge tips described in the previous paragraph, the pole shim thickness was adjusted. A much improved, numerically machined G-11 pole spacer was used for the first time in magnet Z. The width of this spacer was adjusted to match the thickness of the pole shims at the feed end a procedure that was not carried out on the return end of the magnet.

iii) Z cap. The Z cap, the insulating strip providing additional insulation between the coils and the collars did not properly overlap the G-11 pole spacer at the return end. At the feed end it overlapped 1/4" as specified.

This appears to have been due to an error in the way the drawings from the previous magnet, magnet X, were revised for magnet Z. The drawings used by the assembly technicians showed no overlap.

B) The committee identified several other design flaws and concluded that some were completely unrelated to the failure and others were believed to bear on it only indirectly.

i) • Build up of radial thickness when the ends were filled

- Voltage tap and spot heater wires too large
- Interference between I.D. of coil and beam pipe
- Radial dimensions of coil slightly oversize

ii) Dimpling of venetian blinds

iii) Negative lead expansion joint misaligned with shoe.

iv) Pultrusion sections separated longitudinally

v) Yoke blocks not securely fixed

vi) No weld back-up ring or weld preparation at bonnet weld

In the following paragraphs we discuss there deficiencies in more detail.

i) The beam pipe is normally clamped at the feed end plate and is free to 'float' with a radial clearance of 0.055" except where guides are provided. There are a large number of layered components within the annulus between the well controlled dimensions of the beam pipe itself and the collars. Small errors in the dimensions of these components can quickly result in an undesirable tolerance buildup and a reduction of the clearance, particularly at the ends of the magnet.

Before filling the ends of the coils of magnet Z, the process of stabilizing the ends of the coils by filling them with alumina-loaded epoxy had been tested successfully on a short magnet DSS-02. This magnet had been operated with a beam pipe but no correction coils. The technique for carrying out the filling process was new and had not yet been fully developed. The result was that although the process appeared to have been successfully applied, in fact, the radial thickness of the coils was not sufficiently well controlled and the coils were oversize. The procedure has now been changed and the ends are 'molded' to the correct size.

The presence of spot heater wires at both ends of the magnet and a voltage tap wire at the feed end aggravated the situation. The routing of these wires had not been properly integrated into the design, the spot heater wires were slightly smaller than the nominal clearance and under ideal circumstances would not have caused a problem. The voltage tap wire was larger than the nominal size of the space into which it was inserted.

The lack of a comfortable amount of space around the beam pipe is affected by the design of the trim coils that are wrapped around the outside of the beam pipe. The design and construction of the trim coils is currently undergoing a detailed review, and for the time being the 17 meter magnets are being built with no trim coils.

As a result of the excess radial thickness of the coils and the presence of the additional R&D instrumentation wires, the beam pipe had been compressed and had yielded during the collaring process, and was crimped at both ends. Due to different thermal coefficients and to thermal gradients during cooldown and quenching, relative motion between the beam pipe assembly and the coils would have occurred at the return end since the feed end is clamped. Because of the interference around the beam pipe it is likely that any motion could have caused some abrasion of the insulation. Although calculations indicate that relative motion would occur, due to the extent of the damage, it was not possible to ascertain the amount or the effect of such motion.

The BNL traveler indicates that the cable used to wind the coils was out of tolerance in width. The use of oversized cable should be considered an exception and there should be a clear statement that this is the case.

ii) The azimuthal ridge in the venetian-blind did not appear to have had any deleterious effects. However the ridge is not a design feature and appears to indicate that potentially very large stresses are exerted on the coil insulation at the midplane. The design or assembly features that are causing the ridge should be identified and corrected.

iii) The displacement of the negative lead expansion joint appears to have occurred during shipping. It is unrelated to the failure although it is likely to have contributed to the 'lead events.' A methodology should be developed to resolve discrepancies between BNL shipping documents and FNAL receiving documents.

iv) The motion of the pultrusion was unforeseen and procedures to correct it are already being implemented.

v) The question of whether or not the yoke blocks move during cooldown or operation has not yet been satisfactorily answered.

vi) A weld back-up ring behind the bonnet weld could serve two purposes. It would facilitate disassembly since the underlying yoke block would not become fused to the weld, and in a case where the end yoke block is made of carbon rather than stainless steel, would be required in order to prevent contamination and to develop a full strength weld. The lack of a backup ring in magnet Z was not a deficiency since the magnet design requirements did not specify the need to disassemble the magnet, and weld contamination was not a factor. However, the committee recommendation stated elsewhere in this report, that several more R&D magnets be disassembled for inspection, and the possibility of reassembling magnets following modification, would indicate that the inclusion of a back-up ring in the design would be beneficial.

The micrographic examination of the weld itself, indicating lack of weld fusion, is a deficiency that requires correction. The weld preparation of the skin to bonnet interface is being redesigned.

In addition the trauma due to several skin cuts and several collarings, while not a design flaw, had a deleterious impact on the magnet.

5) *General Discussion and Further Recommendation*

- Magnet DD000Z failed catastrophically, but it had undergone significant testing and had already demonstrated improved performance over earlier long magnets. The failure provided the impetus to disassemble and inspect a magnet that had undergone a full operational cycle, and in so doing to gain valuable information that would not otherwise have been obtainable.
- The committee recommends that other long magnets in the program be similarly dismantled under the supervision of other committees, and further recommends that features be incorporated into the design of the magnet that would facilitate the disassembly itself and the understanding of the magnet parameters found during the disassembly.

- The failure illuminates the fact that the magnet is extremely complex with very forceful interactions between components. Thus there is a risk in making changes, particularly last minute changes, if they are not completely integrated into the design.

- In this case a very large number of changes was made and several concepts new to long magnets were incorporated into the design. Many of the new developments although they will eventually result in improved performance, had not yet been studied in sufficient detail to yield results that could be assured of meeting requirements. Taken in conjunction, several deficiencies contributed to the problem of overstressed insulation at one location.

- Tests of the insulation system following the disassembly indicated that 13 of the 16 turns withstood 1 kV in air, the remaining 3 turns failed this test. In an R&D situation it is difficult to untangle whether this was caused by mechanical imperfections, by marginal insulation or by a combination of both.

- No convincing explanation was found for the cause of the lead events. However, they do not appear to be associated with the cause of the failure.

- The cold mass skin weldment is designed for one-time assembly. A magnet that is opened after welding is therefore likely to suffer some trauma that it is difficult to quantify. During the final disassembly and inspection of magnet Z, after the failure, the philosophy of one-time assembly meant that it was very difficult to compare new findings with the uncertain conditions that had existed at the time of final assembly. It was not known if dimensions that were not in accordance with the assembly drawings had been affected by the multiple assemblies or by the operation of the magnet.

6) *Operational Considerations*

Based on the experience with magnet DD000Z, there are several aspects of the test procedure which we recommend be modified to provide additional diagnostic information and prevent non-quench related (unnecessary) trips. Three immediate improvements are:

1) The review of data between magnet excitations should be expanded to include the ground current plot and examination of the 1/4 coil voltage plots over the entire measured time interval.

2) As part of the quench summary, the online program should be modified to include a check of the ground current following quench detection.

3) Additional filtering of the power leads safety circuit signal would suppress transients while still allowing sensitivity to the steady growth of voltage from a quench.

In addition, in upcoming tests there will be significant increases in instrumentation: multiple voltage taps on individual coil turns and additional strain gauges, extensometers, and related devices. The on-line and off-line analysis programs should be modified to provide prompt feedback about the mechanical and electrical state of the magnet from the new sensors during the time between quench tests.

Within the constructs of the present test program (which is certainly more advanced and better instrumented than any previous superconducting accelerator magnet program), it is hard to envision significant improvement at the test phase (other than the relatively minor changes mentioned above) without a substantial change in mode of operation and attendant distortion of schedule and resources required. A far more detailed analysis of the data between quenches or more diagnostic tests of the magnet system, such as inductive measurements of the quarter coil voltages between quenches, could be envisioned. However these changes would stretch the testing schedule significantly and require more people familiar with both the test setup and the data analysis to accomplish these goals in a reasonable time period.

Based on the accumulated experience with the test program, and with the level of instrumentation presently available, it is not clear that the detection probability for problems encountered thus far in the program could be materially improved.

Documentation

While the creation of an effective traveller is a major task requiring substantial manpower, in an R&D program of this nature where each of the magnets may incorporate several new features, the traveller is of the utmost importance. It serves as a means of recording and transmitting detailed information about the construction of each magnet, as well as a means of monitoring and recording quality control procedures.

In Section IV some deficiencies in the traveler were described and it is clear that a considerable effort needs to be devoted to improving this and other magnet documentation. A committee under the chairmanship of Dr. A. Greene has undertaken this task at BNL.

The present committee recommendations concerning the traveler are that it should be a complete, stand alone document that contains all pertinent construction and assembly information about the magnet. In particular the traveler should contain definitions of the criteria by which acceptability is established at each stage of the assembly. Assembly and QA procedures should be specified elsewhere, but the traveler should be the final acceptance document at each stage of the assembly.

Since three national labs participate in this endeavor, there should be input from all three labs:

LBL	–	conductor and cable information
BNL	–	coil winding and magnet and cold mass assembly
FNAL	–	cryostating and testing

1. *Format*. The document should be arranged in several sections, with an index. For example, coil winding and assembly, trim coil/beam pipe assembly, collar coil assembly, yoke assembly, etc. on up to testing. Each section should contain complete details, log records, material records, etc. pertaining to the section. A summary sheet for each section would be helpful in sorting through the details.

2. *Noted Ommissions*. The traveler should make reference to the relevant drawings and written procedures; for instance referring to the coil insulation scheme, yoke assembly, etc. The various sensor identifications, locations and calibrations should be included. Coil lengths, particularly as-finished lengths after

collaring and yoke assembly, were not found. Beam pipe information, including any possibile interferences with the coil or dimples, were not noted on the BNL traveler.

In addition, it will be desirable to include as part of the traveler at BNL a tabulation of measurements and a calculation demonstrating that there is clearance between the coil i.d. and beam pipe/trim coil o.d. for each magnet.

3. *Interfaces.* Disjoints in the data are seen at the interfaces between the labs. For instance at the LBL-BNL interface, which is in the area of the conductor/cable, the cabling records were not included in the traveler. At the BNL-FNAL interface, there is no cross referencing of data.

The FNAL receiving inspection should note any abnormalities and discrepancies and if these abnormalities have not been signed-off before release from BNL, the cognizant person at BNL should be informed and appropriate action taken.

4. *Exceptions.* Where components or assemblies are found to be out of tolerance or otherwise deficient in some way, it may, after review, be decided to proceed with their use. Such exceptions should be clearly stated and some indication or reference given for their acceptance.