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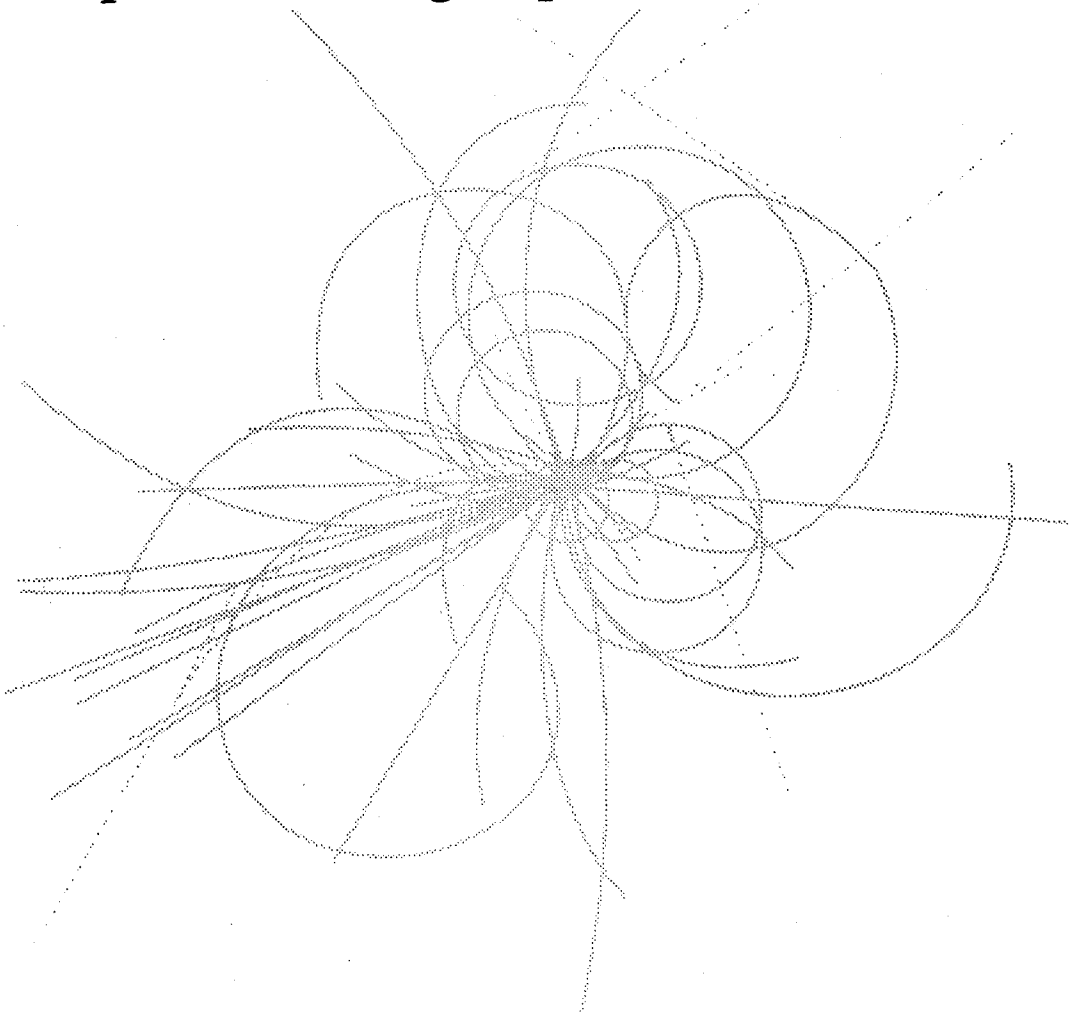

Transportation Studies: 40-mm Collider Dipole Magnets

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March 1992

To be published in *Supercollider 4*

SSCL-Preprint-43

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*Presented at the International Industrial Symposium on the Super Collider, New Orleans, March 4–6, 1992.

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

TRANSPORTATION STUDIES: 40-MM COLLIDER DIPOLE MAGNETS

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ABSTRACT

Several fully functional 40-mm Collider Dipole Magnets (CDM) were instrumented with accelerometers to monitor shock and vibration loads during transport. The magnets were measured with optical tooling telescopes before and after transport. Changes in mechanical alignment due to shipping and handling were determined. The mechanical stability of the cryogen lines were checked using the same method. Field quality and dipole angle were measured warm before and after transport to determine changes in these parameters. Power spectra were calculated for accelerometers located on the cold mass, vacuum vessel, and trailer bed. Where available, plots of field quality and dipole roll both before and after were created.

Shipping loads measured were largest in the vertical direction, where most of the structural deformation of the magnet was evident. It was not clear that magnetic performance was affected by the shipping and handling environment.

INTRODUCTION

CDMs will be transported by truck from vendor production facilities to the acceptance location prior to installation both in the Accelerator Surface String Test (ASST) and in the Collider Ring. It is important to ensure that the CDMs can be "safely" transported. "Safely" is defined here as maintaining comparable mechanical integrity and magnetic performance before and after shipment.

Early work[1] consisted of transportation and vibration computer models that attempted in part to predict the response of a CDM to transportation loadings. Earthquake Engineering (EQE) used input for these models that were formulated from actual test data taken from road tests conducted on large shipping containers (gross weight roughly 39,900 kg) at Sandia National Laboratories.[2] Maximum accelerations for several different road conditions were less than 1 g for all events, and RMS loads were not greater than 0.25 g. The report

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recommended that actual testing of the final trailer mounting configuration was required to verify this work.

An in-depth transportation study was then conducted by Vibration Engineering Consultants (VEC) at Fermi National Accelerator Laboratory (FNAL) on a 40-mm dipole DSHIP.[3] DSHIP is a dedicated transportation and vibration prototype, with accelerometers and strain gages permanently installed, intended for structural and dynamic studies. This test was geared toward measuring shock and vibration loads during transport. Several mounting schemes were investigated. A set of mounts that attached the magnet to the trailer were built, as well as an axial restraint that served to couple the cold mass to the vacuum vessel at the return end of magnet.

Initial results showed that the existing method of transport would indeed compromise mechanical alignment of the magnets, but correlation in terms of vibration response between the actual test data taken by VEC and the computer models developed by EQE was poor. The mechanical data taken showed deformation of the magnet, but in a qualitative sense only. Deformations were observed, but the magnitudes were not determined, and the mechanisms causing the deformations were not identified.

Another series of transportation studies were conducted in the interest of learning more about the magnet's response to shipping and handling. Particular attention was paid to quantitatively determining the deformation of the magnets due to the transportation environment. Magnets DC0202, DC0201, and DD0028 were transported between FNAL and Brookhaven National Laboratory (BNL). Studies on these three magnets were conducted not only to measure dynamic loads during transport and to qualitatively identify structural changes caused by transport, but also to quantify changes in magnetic field quality if possible.

Results from these studies are contained within the body of this report. Acceleration spectra are consistent with earlier test data. Natural frequencies of the magnet-trailer system correspond well with those predicted by computer models created at SSCL.[4] Mechanical deformations of the vacuum vessel are as great as 1 mm in the vertical direction. Measurements of the change in location of the cryogen lines show displacements of the order of 5 mm. Warm magnetic field quality and dipole angle measurements were taken before and after transport for DC0202. Values of the magnetic multipoles and dipole angle were determined versus position along the length of the magnet.

TESTING EQUIPMENT AND PROCEDURES

The magnets were instrumented with 14 accelerometers placed on the cold mass (CM), vacuum vessel (VV), and trailer bed (TB) to monitor accelerations in as many as three directions. The vertical direction (V) is aligned with gravity, the axial direction (A) is aligned with the magnet centerline, and the horizontal direction (H) is orthogonal to the vertical and axial directions. The accelerometers were attached to both the lead and return ends of the magnets as shown in Figure 1.

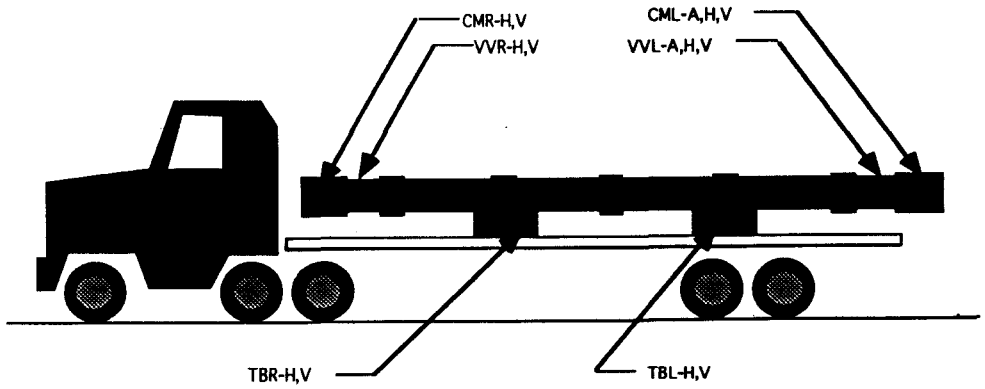

Figure 1. Accelerometer Locations During Transport.

The accelerometers were PCB 308 units with a nominal output of 100 mV/g and a resolution of 0.001g. PCB 483A07 amplifying power units were used to supply power to and amplify output signals (×10) from each of the accelerometers. The amplified signals were then fed to a Kyowa Dengyo RTP-650A 14-channel tape recorder, which converted the time-varying voltages to frequency-modulated data. The signal-to-noise ratio on the FM band used was 41 dB_{rms}.

In order to power the transducers, amplifiers, and data logger, a 2.2-kW portable gasoline-powered generator was attached to the trailer bed. The units that required 110 VAC were connected to the generator through a surge suppression strip and were contained in a weatherproof box mounted to the trailer bed.

The accelerometer signals were recorded to tape during the entire trip of ~950 miles, covering a variety of road conditions and speeds. The tape-recorded time signals were fed into an HP 3567A Spectrum Analyzer controlled by an IBM PC. The time histories were converted to power spectral densities (PSDs) using a uniform window over a 4-sec time record. The analyzer was set for a range of 0–200 Hz using 800 frequency lines, resulting in resolution of 0.25 Hz. Using a peak hold type of measurement, the analyzer recorded the largest value of acceleration for each frequency line over the 100-Hz range for the entire trip.

The magnet was attached to a 55-ft air ride trailer using a pair of magnet mounts developed at FNAL, consisting of a combination of inflatable air bags that supported the magnet at its external feet locations. These mounts were used for early transportation studies, moving magnets from building to building on site at FNAL, and cross-country trips between FNAL and BNL. The total weight of the magnet and trailer was less than 20,000 kg.

An axial restraint that rigidly coupled the cold mass to the vacuum vessel during transport was used as well. This restraint was designed to allow the long-term, or slow, motions such as thermal contraction or expansion while restricting the relatively short-term, or fast, motions such as impulsive forces associated with shipping and handling.

A pair of endbells sealed the magnet from the environment. BNC feed-throughs routed the cold mass accelerometer cabling from the sealed interior of the magnet to the tape recorder. The magnet was backfilled to positive pressure with gaseous nitrogen and set to purge during transport.

None of the magnets were temperature controlled. The shipment dates and average temperatures are shown in Table 1. The upper limit on temperature for the magnets is 30°C. It is obvious from looking at the temperature ranges that this was not a problem.

Table 1. Magnet Temperature During Transport.

Magnet	Dates of Travel	Average Temp. (°C)	Maximum Temp. (°C)
DC0202	12/19-12/20/90	0	5
DC0201	1/29-1/30/91	5	10
DD0028	3/19-3/20/91	0	5

A series of tooling balls were placed at the five reinforcing rings, numbered 1 through 5 from return to lead end, on the vacuum vessel, and the end rings on both the lead and return ends. The cross section (Figure 2) shows seven tooling balls at each location, A–F. At the return end of magnet DD0028, four tooling balls were welded to the cryogen pipes and were labeled H, J, K, and L. The positions of the tooling balls were measured vertically and laterally using several jig transits and a pair of tooling bars. The same workers and set of instruments were used to measure the magnet both before and after transport.

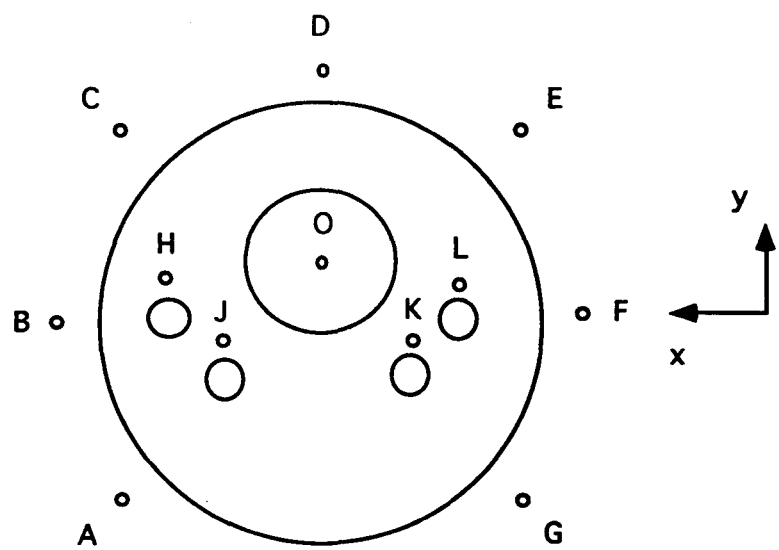

Figure 2. Tooling Ball Locations at Return End of DD0028.

A tooling ball network was generated from each data set. Two points from each data set, points 4F and 2F, were chosen as coincident, and a third point, 4B, was chosen as co-planar. All other points in the data sets were rotated accordingly.

Two types of magnetic-field quality probes called moles were used to perform these measurements. At FNAL prior to transport, the B2 mole logged multipole values and dipole angle at 28 positions along the magnet's length. At BNL after transport, the D1 mole logged the same values at 17 points along the length. One major difference between the moles was the dimensions of the rotating coil that senses the magnetic field. The B2 mole (FNAL) has a 24-in coil, while the D1 mole (BNL) has a 1-m coil. Another difference is the diameter of the rotating coil. The D series had a smaller diameter due to more insulation between the coils and the measuring device.

RESULTS AND DISCUSSIONS

Table 2 illustrates the types of tests conducted on each of the three magnets. It would have been most desirable to conduct all of the tests listed below on all three magnets, but schedule constraints and function at destination precluded conducting the full array of tests on the trio of magnets.

Table 2. Magnet Measurement Matrix.

Measurement	DC0202	DC0201	DD0028
Dynamic Loads	√	√	√
Mechanical Alignment	√	x	√
Cryogen Line Alignment	x	x	√
Warm Magnetic Measurements	√	√	√
Cold Magnetic Measurements	x	x	x

As mentioned earlier, the accelerometer time histories were converted to PSDs using the spectrum analyzer. A PSD is a graphical representation of values of power density versus frequency, and it represents the distribution of vibration energy with frequency. The PSDs are important results, and they provide useful information to the designer of a shock and vibration isolation system.

Generally, the transportation environment was comparable to the studies mentioned in the introduction. Acceleration spectra measured in the vertical direction were the largest, roughly ± 1 g incident to the cold mass. The dynamic displacements of the entire structure on the trailer bed were of the order of several inches. This displacement was due to the air bag suspension system that held the magnet to the trailer bed. Axial and horizontal spectra were of the order of ± 0.5 g, which were well below design parameters. Specifications for the 40 mm design B cryostat required ± 2 g vertical, ± 1.5 g axial, and ± 1.0 g lateral. However, this dynamic environment caused the vacuum vessel to change shape. This suggested that another mechanism caused the magnet to deform.

Tooling ball locations were measured with respect to a pair of tooling bars both before and after shipment. Three points on each magnet were rotated to reside in the same plane to facilitate a comparison of changes in mechanical position. This mathematical operation minimizes errors associated with instrument set-up, and allows for comparison of position of magnet components both before and after shipment.

The overall change in elevation of the magnet is shown in Figure 3. The magnets exhibited a bowing downward of roughly 0.25 mm at the midpoint. The final shape was coincident with the first vertical mode of vibration of the magnet, as can be seen in the PSD plots given earlier. This shape change was most likely due to the method of support used during transport. Note that the beam tube, point O, was displaced by roughly 1 mm from its original position. This change was attributed to the installation and removal of the axial shipping restraint that was attached to the return end of the magnet.

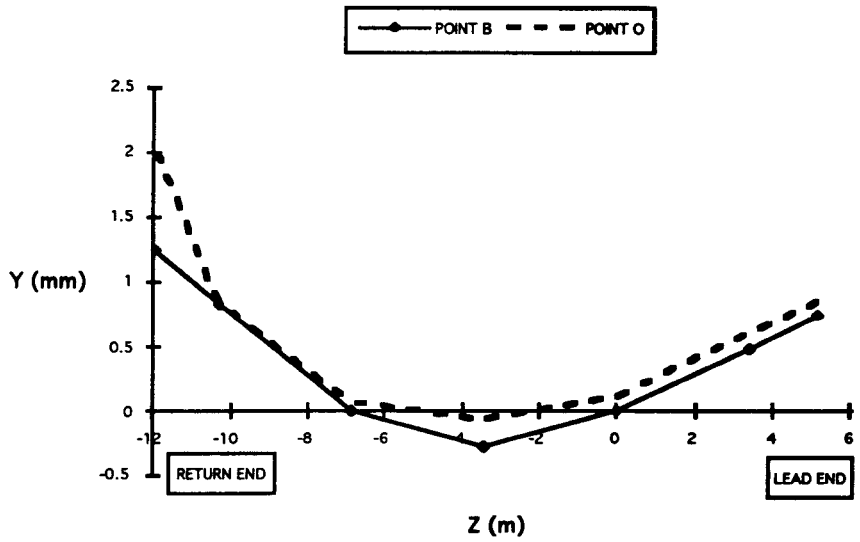

Figure 3. Change in Vacuum Vessel & Beam Tube Vertical Position.

Questions were raised regarding the integrity of the folded path posts during transport. It was thought that the shock and vibration environment would cause the posts to fatigue and yield, resulting in misalignment of the cold mass within the vacuum vessel. Figure 4 illustrates the change in radial position of the beam tube centerline with respect to the vacuum vessel exterior at post #1. The beam tube centerline and consequently the cold mass position within the vacuum vessel were preserved, although the overall position of the reinforcing ring was changed. Changes in lateral position were within the tolerance of the measurement devices or slightly greater. Little change was expected due to the minimal dynamic inputs experienced during the trips.

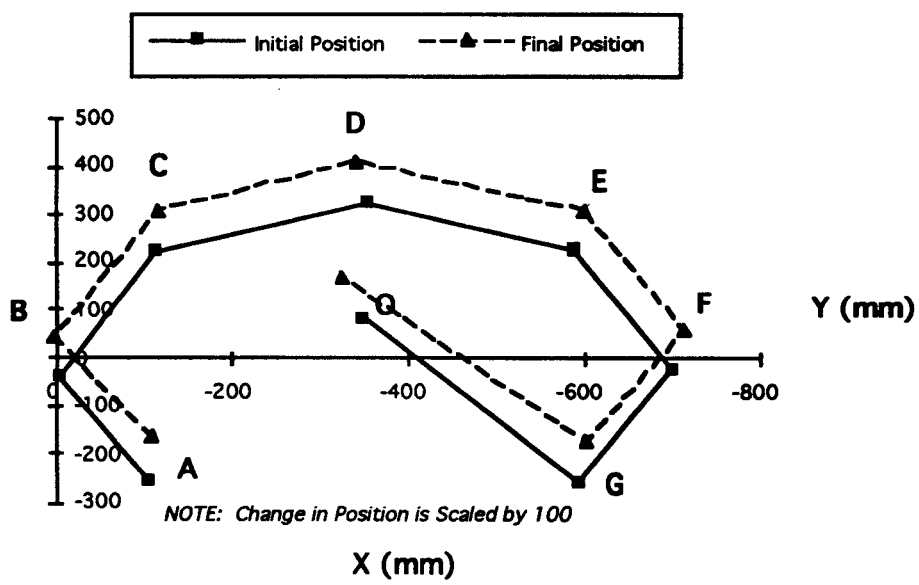

Figure 4. Change in Radial Position at Post 1.

The overall change in location of the cryogen lines (see Figure 5), as much as 6 mm vertically at the end of the magnet, was due in part to the change in shape of the vacuum vessel. Structural instability—twisting of the thermal shielding—accounted for most of the permanent displacements. The cryogen lines and shields experienced permanent deformations of as much as 4.5 mm vertically and 0.5 mm laterally with respect to the beam tube centerline. These motions were independent of the change in shape of the vacuum vessel.

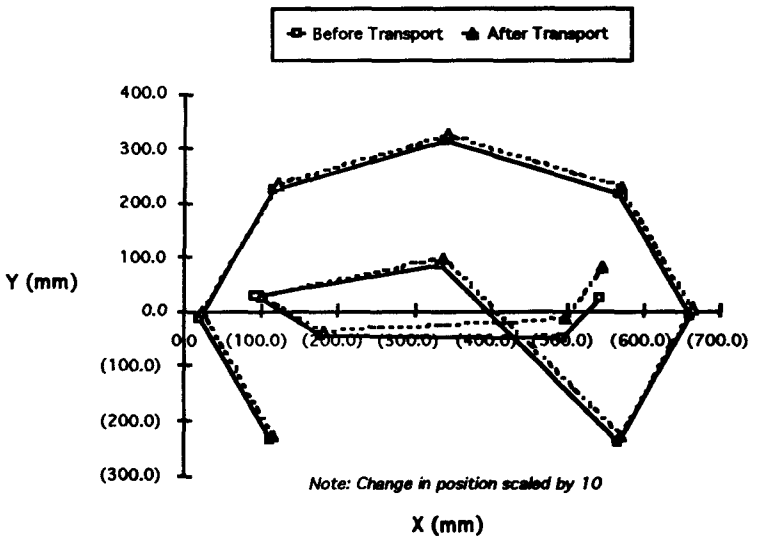

Figure 5. Change in Cryogen Line Location at the Return End of DD0028.

Measurements of magnetic field quality were conducted both before and after transport. Figure 6 shows the results of a warm Z-scan conducted both before and after shipment. These data were taken from the DC0202 study. Wanderer[8] indicated that these changes should be viewed as upper limits to changes in multipoles due to transportation.

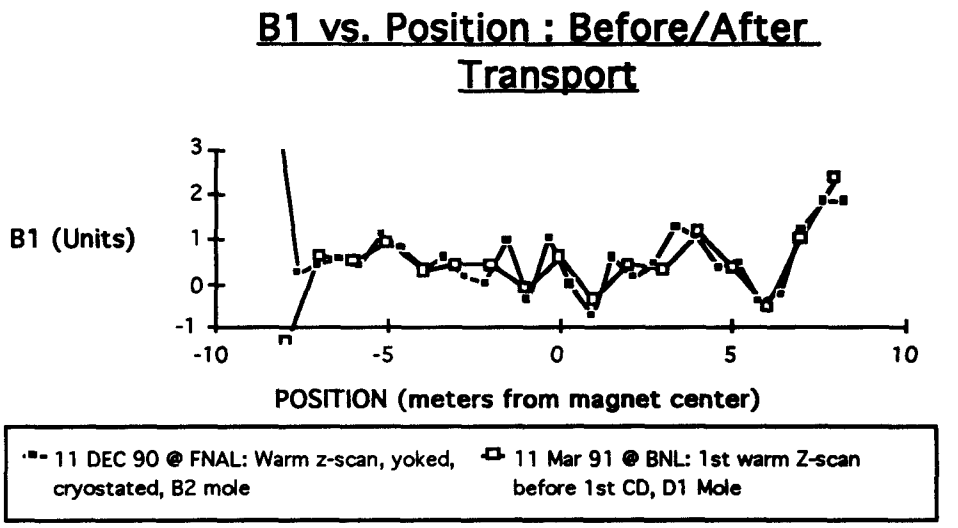

Figure 6. Warm Z-scan Before and After Shipment.

Figure 7 plots dipole roll angle both before and after shipment along the length of the magnet. There is a definite shift between the data sets of roughly 10 mrad. It was most likely an instrumentation bias due to the differences in construction between the two moles that were used to obtain the measurements.

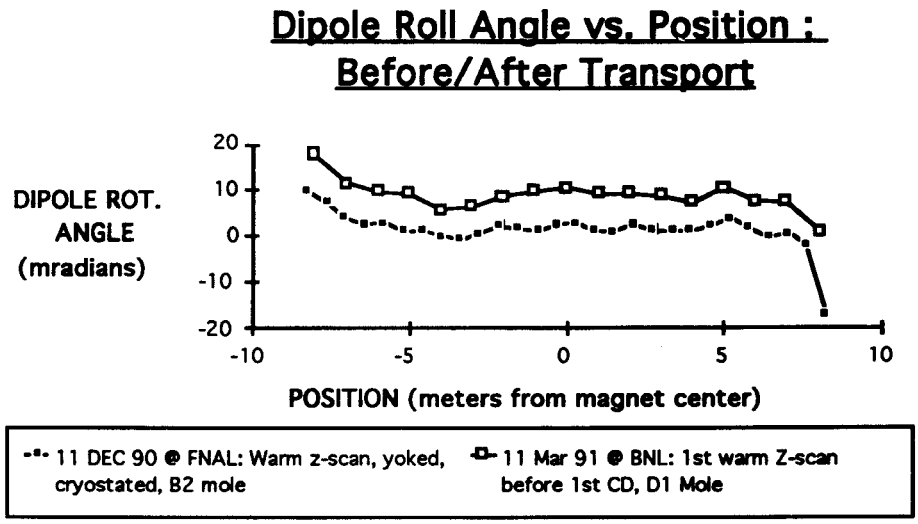

Figure 7. Dipole Roll Angle Before and After Shipment.

CONCLUSIONS

The 40-mm design B vacuum vessel design is compromised by the shock and vibration environment experienced during transport. The magnitudes of the PSDs show relatively low vibrational energy transfer to the magnet when compared with earlier studies conducted on DSHIP and DD0018. The vertical accelerations were largest—of the order of 1 g incident to the cold mass.

The deformation of the magnet in the vertical direction is greater than acceptable limits. This deformation, primarily the vacuum vessel, is due to the present trailer-mount configuration and weld relaxation at the reinforcing rings.

The compact cryogenic support posts withstood the transportation environment and maintained the cold mass position with respect to the vacuum vessel reinforcing rings at each of the five support post locations within 0.125 mm.

The present shield assemblies do not withstand the transportation environment and deform by as much as 6 mm in the vertical direction.

Magnetic measurements have provided an upper limit on the changes of multipoles due to transportation. To better understand these changes, measurement equipment with improved accuracy must be developed.

FUTURE WORK

All transportation studies including this one have been conducted with 40-mm magnetic aperture CDMs. The baseline design for the ASST and consequently the Collider Ring has been changed to 50-mm aperture CDMs. Therefore, studies should be conducted with 50-mm CDMs, which are 25% heavier with a different vacuum vessel design. These studies should begin with an improved method of support of the magnet during shipment.

Transportation issues will be extended to the many other types of magnets that will be installed in the Collider and High Energy Booster as well. Studies conducted on other magnets will provide insight into the variety of shipping problems that may be encountered.

ACKNOWLEDGEMENTS

The author would like to thank both M. Ruschman of the InterGalactic Engineering Lab, who was involved with the technical aspects of many of the early studies conducted at FNAL, and D. Sorensen for their assistance with setting up the studies.

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