In-Situ Non-Destructive Testing of Superconducting Dipoles in the Tevatron,

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Since the commissioning of the Tevatron in 1984 there have been a number of magnet failures. Most of the failures were caused by conductor motion at the magnet ends during field ramping. We describe visual and x-ray methods that were used to identify those magnets in the tunnel that showed incipient damage and were likely to fail later. These magnets were repaired in the tunnel and returned to service. The visual method used a fiber optic bore scope and could only be used at room temperature. The x-ray method used a collimated radioactive source and could be done on warm or cold magnets. The combination of these methods gave us information on placement and constraint of the conductor in the magnet ends. Results from a nine week repair period are presented.

INTRODUCTION

Since 1984 we have known that the superconducting leads coming out of the collared coil of Tevatron dipoles experience a force during ramping which may cause the cable to flex if the leads are not tied together. This flexing can result in broken superconducting strands. The eventual consequence is a catastrophic failure of the magnet. In addition several other modes of failure have manifested themselves over the years and originate in the end cans of the magnets. By the end of the 1987 fixed target run it was apparent that repairs on the magnets would be required but it wasn't known which of the 778 dipoles needed to be repaired.

MAGNET ENDS AND FAILURE MODES

Figure 1 shows Tevatron dipole ends .

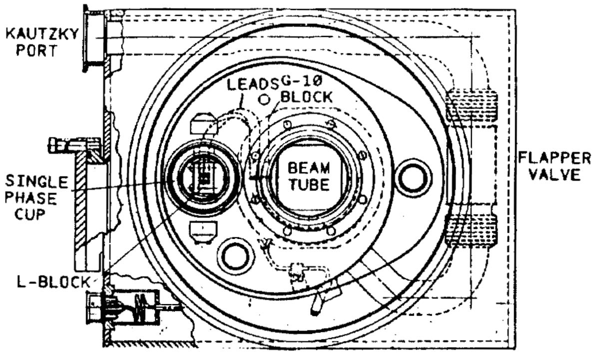

Fig 1. TeV Dipole end

There are two types of dipoles; TC and TB. The difference between the two is that the collared coil is rotated 180 degrees in a TC magnet. This results in a much longer length of cable in the end cans. It is because of this longer lead that the TC's were the first to fail when the leads were not tied. During the 1984 shutdown all TC upstream ends were repaired. It was realized that the TB magnets suffered from the same problem but had yet to fail. It wasn't until three years later (through two fixed target runs and one collider run) that TB's started to fail. Table 1 shows a chronology of failures during the 1987 fixed target run.

Table 1. Chronological order of magnet failures

Magnet	Location	End	Date	Failure
TC 461	A27-5	DN	7/18/87	Broken leads
TC 632	E48-3	DN	9/25/87	Broken leads
TC 463	E33-5	UP	10/12/87	Cracked weld (vac)
TC 550	B18-4	DN	10/27/87	Broken leads
TC 767	E46-2	DN	11/27/87	Grd flt to beam tube
TB 341	E25-2	UP	12/04/87	Broken leads
TB 359	A32-4	UP	12/14/87	Broken leads
TB 280	E12-3	UP	12/14/87	Vac. leak

A disturbing feature of this table is that the downstream ends of TC magnets were failing in the same way the upstream ends had. In the 1984 repair only the upstream leads were repaired as they were known not to be tied. It was thought that the downstream end leads were correctly restrained since it was general practice to tie all the instrumentation wires to the magnet leads.

A second problem indicated in Table 1 concerns vacuum failures. It is now thought that these failures are a result of cryostat motion during ramping. Measurements and calculations from Carson et al. [1,2] indicate that the length of the collared coil assembly increases by ~100 mils during excitation. The coil assembly is restrained at the center, thus anything mounted on the collared coil must be roughly 60 mils away from the end can. The closest gap is at the G-10 block which clamps the leads where they enter the collared coil. If this block was closer than 60 mils to the end flange then during excitation it would move into the flange and flex it outwards. Continued flexing would result in a crack in the weld which holds the end flange to the single phase can.

The final problem indicated in Table 1 is a coil to beam tube ground fault. This problem has been seen when a section is warmed to room temperature and later hipotted. The beam tube is insulated with an adhesive backed kapton tape. This beam tube is in close proximity to the coil windings; if the insulation were to be damaged in any way this proximity could lead to a ground fault even under liquid helium conditions. The adhesive which holds the kapton tape to the beam tube disintegrates in liquid helium and, under flowing conditions, the tape unwinds.

FIBER SCOPING

Our first inspection tool was a flexible fiber optic industrial bore scope used to obtain a real color, clear view of the magnets. This was only possible at locations where the magnets were warm. With the bore scope we could determine 1) type of insulation used on the leads, 2) whether screws or rivets were holding the L-Block together, 3) whether the leads were tied and if so with what (Kevlar string or nylon cable ties), 4) whether there was foreign material in the single phase and 5) whether

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the kapton wrap on the bore tube was intact. Pictures were taken at each location for careful viewing at a later time.

We used an Olympus IF7D3x3-26 7mm fully articulated fiberscope. This instrument contains a working channel enabling the operator to carry out some simple manipulations with a small hook at the end of the scope. The length of the bore scope was 3 meters. The light was an external high intensity Halogen source. The light source fiber bundle, the image fiber bundle (which contains 25000 optic fibers) along with the two cables for articulation are all contained in a 7 mm diameter stainless steel braided jacket. After several hundred operations some fraying of the jacket was noted and some individual fibers were broken.

Pictures were taken with a Olympus OM4T 35mm camera, mated to the borescope eyepiece. ASA 400 color film was used but shot at the 200 speed . There was, between the film and the 3 meters of fiber optics, a color shift toward the green evident on the prints. This was corrected during the film developing stage by increasing the green filtering and decreasing the yellow filtering. The result was very true color reproduction. A data back was used to put the magnet serial number on each picture.

The downstream end of each magnet was accessed by removing the helium relief valve. About 9" into the magnet is a flapper valve that had to be lifted in order for the borescope to pass through into the rest of the magnet. This was done using a small suction cup and some tubing. Once the flapper valve was lifted the scope was snaked down into the magnet to the various locations of interest. The working channel was frequently used as a scale. The known diameter at the end of the probe was pushed into the field of view, and then inserted between the G-10 block and the end flange of the single phase. In this way an estimate of the clearance could be obtained. The best set up found was to look through the camera that was mounted on a substantial tripod. This would free the operator's hands for both the scope articulation adjustments and feeding the scope into the magnet. In locations where the single phase interface had been opened up, upstream pictures could be taken as well. This was done by entering through the single phase cup where the leads are located.

X-RAYS

A second inspection method was x-rays. This method works with both warm and cold magnets. The x-rays were produced by a 100 Curie Iridium 192 source encased in a stainless steel capsule. When not in use this capsule was housed in a Uranium/steel 'camera'. For placement of the source a flexible tube was used. One end of the tube was attached to the camera and the other end was taped to a stand and placed above the point of interest. A steel collimator was also placed at this end in order to absorb x-rays not aimed at the region to be exposed, thus making a clearer image at the film. The film used was DuPont 65 with an exposure time of 1 minute. To identify which magnet was being x-rayed, lead letters were placed on the film indicating the magnet number, location and date.

The primary information we could get from the x-rays was : 1) information on the G-10 block including its clearance to the end flange, the kind of screws used and whether or not the block was coming apart, 2) information on the L-Block (which constrains the leads going into the single phase can) including what held it together(rivets or screws) and was it coming apart and 3) were the leads separated, indicating they were not tied.

To get this data required two sets of shots. To get the best pictures the source needed to be aligned directly above the object of interest. The placement was most crucial for the G-10 block. This was because the clearance was usually less than 100 mils. Any misalignment could cause the end plate to overshadow the clearance (due to parallax) and result in large errors. To do these shots a nominal distance from the magnet iron laminations was chosen from tests. One shot was taken at this nominal distance and a second shot was taken 1/8 inch away. Alignment was quickly done using a plumb bob and a "notched" ruler. For the lead shots the placement was less crucial due to the larger area and only one shot per magnet end was done.

A second parameter of importance was the source to film distance. The greater the distance the less magnification that occurred and the clearer the picture. Unfortunately this distance was limited to a maximum of 24 inches due to the Main Ring magnets. This gave a magnification of approximately 50% which was taken into account in our analysis.

The quality of the images is also a function of the amount of material which must be penetrated. The upstream end of the dipoles has less material between the source and the film than the downstream end. The consequence of this is that to x-ray the downstream end required the interface between magnets to be opened up. This was not difficult to do but it did require the insulating vacuum be let up to atmosphere. This meant we could only x-ray the downstream end of warm dipoles whereas the upstream end could be done warm or cold. An average of 30 magnet ends could be shot and all pictures developed and ready for analysis in one 8 hour shift. Due to the high radiation levels and associated precautions, x-raying was done only in the evenings. For personnel saftey lead shields were rolled along and placed 50 feet away from the source. By use of the lead shields exposures were kept low; on average 10 mrad per shift (without the shields the x-ray technicians would have received approximately 70 mrad in one shift).

RESULTS

A total of 200 dipoles were inspected. Table 2 is a synopsis of what was found.

Table 2. Tabulation of the inspection data obtained during the shutdown

	TB Upstream	TB Dnstream	TC Upstream	TC Dnstream
# of ends	104	104	96	96
Leads not tied	85	22	0	28
Broken strands	7	0	0	0
L-Block loose	13	8	2	11
G-10 block loose	22	25	24	12
G-10 clearance	21	29	21	25
Beam tube Kapton	48	0	0	0
# x-rayed	104	103	94	95
# bore scoped	104	84	8	78

The primary purpose of these tests, to determine which magnet leads were not tied, was mainly accomplished using the bore scope. Supporting data as well as information on the leads at the upstream end were obtained by x-ray analysis but only as to whether the two leads were separated (the x-rays could not image the ties). Of equal interest, especially since we were not repairing the entire ring, is to try to determine if a magnet has broken strands. Neither method of inspection was capable of directly finding broken strands. An indirect method was to use the x-rays to determine how much the leads were separated. We would expect broken strands to occur in magnets that have : 1) large lead separation 2) been in the tunnel a long time and 3) G-10 block or the L-block with sharp edges (the broken strands were generally found to be at one of these places since they are the two points where untied leads would be constrained). A further constraint could be added by looking at the serial numbers of all the magnets which have failed, including the TC magnets that failed in 1984; all the failed magnets had serial numbers below 800 (magnet numbers in the tunnel ranged from 200 to roughly 1160). Figure 2 is a plot of lead separation vs serial number for the set of magnets which were repaired.

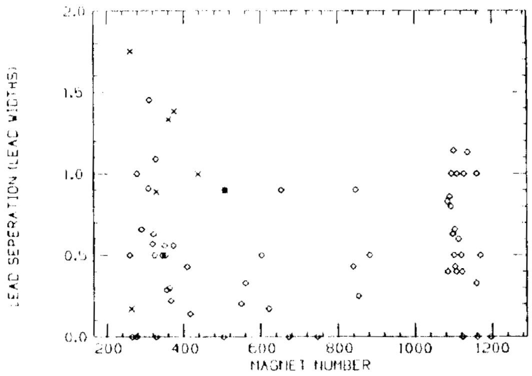

Fig 2. Lead seperation vs magnet serial number

The x marks indicate magnets with broken strands. The lead separation is in units of measured lead widths (this was done to avoid taking magnification factors into account). From this plot if we make a cut above 75% lead separation and magnets below # 800 there are a total of 12 magnets of which 6 had broken strands. Notice that for magnets above 800 no broken strands were found (presumably because later magnets had the L-blocks and G-10 blocks tumbled to eliminate sharp edges).

Fig. 3 below compares the calculated clearance with measurements made during repair.

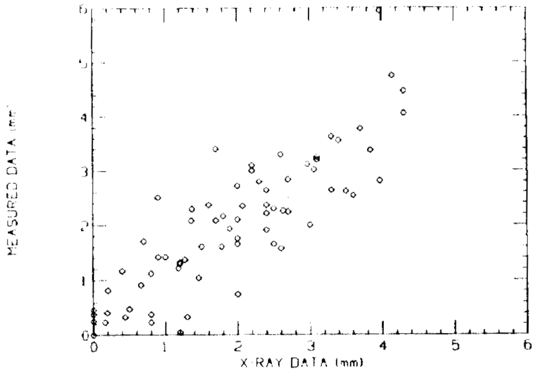

Fig 3. Measured vs Calculated clearance

For determining clearances, an equation was derived which took into account the magnification factor and any parallax due to the source not being directly over the gap. After choosing the best picture for a given end three measurements were made: 1) the visible clearance from the G-10 block to the end plate, 2) the G-10 block size (to determine the magnification factor; the block is one inch wide) and 3) the measured width of the end plate. From these three numbers the actual clearance was calculated. In addition bore scope data was sometimes obtained which gave us an additional source of information on the clearance (getting to the G-10 block wasn't always possible especially on the TC's). Although we couldn't measure a distance via the bore scope we could determine if it was greater than the working channel scale. Comparing the measured clearance with the bore scope data we find only three cases out of 50 where there was a discrepancy. Of these the x-ray data was in agreement with the measurement in two cases and in the third case both methods gave significant differences from the measured value.

Two other problems alluded to in Table 2 concern the L-block coming apart and Kapton insulation on the beam tube. Of all the TB upstream ends (the downstream ends don't unravel because the tape is wrapped around itself) that were inspected 58% were found not to have the Kapton tape tied down with Kevlar string and of those not tied 79% were found to be unraveling. As for the L-blocks the problem was that some were held together by bolts and nuts which were coming undone (we often found nuts and bolts in the single phase can).

Since we have x-rays of the upstream ends of all the magnets there is a considerable amount of data we are using to decide which magnets to repair during the next shutdown. From these we find a total of 372 out of 568 ends which will require reworking. We have in addition made estimates, extrapolating from information obtained during the repair period, for the downstream ends which indicate an extra 326 ends to repair.

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