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**Operational Experience with
Superconducting Synchrotron Magnets***

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OPERATIONAL EXPERIENCE WITH SUPERCONDUCTING SYNCHROTRON MAGNETS

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Abstract

The operational experience with the Fermilab Tevatron is presented, with emphasis on reliability and failure modes. Comparisons are made between the operating efficiencies for the superconducting machine and for the conventional Main Ring.

Introduction

The Fermilab Tevatron began operation in 1983. Most of the operating experience has been in fixed target mode, the first few months at 400 GeV, the remainder at 800 GeV. More recently, some experience has been gained in the Collider mode with the Tevatron operating at 900 GeV. This period of operation has had two extended shutdowns for major construction projects. These shutdowns provided the opportunity to replace components with the intent of improving the machine, both from the reliability standpoint and with the goal of increasing the peak energy of the Tevatron.

The Tevatron consists of approximately 1300 cryogenic devices, as shown in Table 1. The majority of these consist of dipoles, quadrupoles and "spool pieces". The latter contain correction elements, cryogenic instrumentation, and "quench stoppers" which hinder the propagation of quenches from one side to the other. Roughly half of the spool pieces also contain "safety leads" which allow current to be diverted around a cell when a quench occurs. This avoids having the quenching magnets absorb the energy stored in the non-quenched magnets in the rest of the ring.

TEVATRON COMPONENTS

Dipole	777
Quadrupole	224
Spool Piece	206
Feedcan	26
Bypass	22
Turn-around Box	27
Other	11
Total	1293

TABLE 1

Installation and Commissioning

The power tests of sections of the Tevatron, as they were installed and cooled down, have been described elsewhere [1], and this discussion will limit itself primarily to the period of time beginning in July, 1983. A few minor installation problems had occurred. These included (1) a quadrupole which was improperly constructed in a manner which could not be detected in the tests at the Magnet Test Facility (MTF); (2) a turn-to-turn short which developed between MTF tests and arrival in the tunnel; (3) two inter-magnet splices which were not soldered. Only the first of these could be detected prior to cooldown. These problems had been rectified by July, and beam was being circulated in the machine.

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Operation

The initial operation of the Tevatron was at 400 GeV in order to complete the fixed target high energy physics program remaining from the Main Ring operations. The Tevatron had already accelerated beam to 700 GeV, and beam had been "stored" as required for Collider operation, for rather modest storage times. At 400 GeV, the Tevatron was obviously far below its capability. Quenches, transitions from the superconducting to the normal state, were nevertheless a problem. Even at modest beam intensities the magnets will quench at injection (150 GeV) if there is sufficient localized beam loss, as results from a kicker misfiring.

This initial run of commissioning and fixed target physics operation was interrupted by two repair periods. The first, during a scheduled two week shutdown, involved the replacement of three different components. None of those replacements were urgent. The second repair period was to replace eight components which had been damaged in a single episode when the power supplies were not turned off following a kicker-misfire induced quench. This event is described [2] in more detail elsewhere. (Failure to turn off the power supplies resulted in overheating the safety leads to the point that the insulation was damaged and a ground fault resulted.) The remainder of the running period was marked by refrigeration problems, but no further warmups of the Tevatron; thus there was only one unscheduled repair during the first seven months of operation.

In February, 1984, the Tevatron was shut down to install the low beta quadrupoles around the B0 intersection region so that they could be commissioned during the ensuing fixed target run. The experimental areas also needed that time to switch experiments, with the 400 GeV program now completed. During this transition, two additional components in the Tevatron were replaced. Again, these were replacements being done because the opportunity arose, not out of necessity.

The 800 GeV fixed target run began ominously; it began with a magnet failure. Four similar failures followed during the next four months. The Tevatron dipoles come in two types, known as TB and TC. They are four pole devices, with an upper and lower bus which may be far apart electrically. One bus runs straight through the dipole, from one end to the other--one half turn. The other bus forms the remainder of the 110 turns of the dipole. The TB and TC magnets differ in that the TB (TC) magnet has the inductance on the lower (upper) bus. There are also slight mechanical differences in their construction. The TC magnets have about 30 cm of superconducting cable from the magnet to magnet splice to the point at which the conductor leaves the collared coil assembly. The Lorentz force from the fringe field at the end of the magnet produced flexing of the cable as the current was ramped up and down. Individual strands began breaking, and the ends of the broken strands were likely to produce ground faults or bus-to-bus shorts. The last four failures occurred in the span of about six weeks. At that point, the machine was shut down and all the TC magnets were repaired by opening the cryostats and securing the leads together with Kevlar string to prevent motion. This shutdown

would have taken place in any case, in order to construct the D0 overpass and extraction line for the Antiproton Source, but its beginning was advanced by the Tevatron TC problem.

The 1985 run was primarily an 800 GeV fixed target run, but ended with a six week test of the Collider. There were frequent Collider studies interspersed within the fixed target operation. A series of tests were also performed to identify the weakest magnets in each of the six sectors. This run also started grimly. A power supply transformer shorted primary to secondary, placing 13.8 kV onto the Tevatron and damaging five components. The identification of high impedance ground faults is difficult in a superconducting accelerator. The leakage current is small, making inductive measurements difficult. Warming the magnets up slightly, so they are no longer superconducting, helps; the resistance of a cold, but non-superconducting Tevatron dipole is about .1 ohms. Isolating the magnets cannot be done, of course, until the magnets are warmed up completely.

In addition to the transformer problem discussed above, there were four more magnet repair periods during this ten month run. The first was precipitated by a power supply failure which again placed excessive voltage on the magnets. The machine was able to operate in spite of the leakage currents; the Central Helium Liquefier had to shut down shortly after the power supply problem, and that provided the opportunity to replace the affected components. Two of the other failures were similar to the TC problem. One was at the downstream end, where the leads were normally tied together due to the instrumentation leads coming out of the coil assembly at that point. This step was omitted during the construction of the one dipole. The second was apparently caused by some of the strands having been cut during the insulation process of assembly. The other failure of this running period was a cryostat rupture during a quench. This failure began with a spontaneous (i.e. not quench-induced) leak from the single phase helium circuit into the insulating vacuum. The poor vacuum warmed the magnets resulting in a quench when the magnets were ramped again. The quench pressures ruptured the cryostat at the point of the leak.

REASON FOR REPLACEMENT
60 COMPONENTS REPLACED PRIOR TO JULY 15, 1985

Failure During Operation	19
Hipot Problems	8
Low Quench Current	3
Leak	19
Instrumentation	3
Lattice Matching	1
Correction Element	7
Uncertainty	3
Other	4
Total	68

TABLE 2

Table 2 lists the reason for replacement of the 62 components that were replaced during the first two years of operation of the Tevatron. This period of time includes approximately twenty months of operation and five months of shutdown. The category Uncertainty accounts for instances in which two or more components were removed when the source of the problem, e.g. a ground fault or leak, could not be localized to a single device. Of the nineteen Failures During Operation, fifteen were associated with the the safety lead or transformer incidents, or with the TC problem.

There is some double-counting, since some elements had more than one problem.

Higher Energy Excitation

There were a series of tests, beginning in July, 1985, in which individual sectors of the Tevatron were ramped to higher excitation currents in order to probe the energy capability of the machine. They marked the start of what might best be considered a Tevatron improvement program. Three months later the shutdown which completed the last major civil construction for the Tevatron I program began, which afforded the opportunity for significant changes in the Tevatron. In these tests, the weakest component was identified in five sectors. The sixth sector was ramped to 930 GeV without quenching. In some sectors, the weak magnet agreed with expectations based on MTF measurements; in two sectors, the quench location did not to agree with MTF data. Further, the quenches appeared to originate outside of the high field region of the magnet, as indicated by the relatively slow growth of the quench. During the shutdown to install the Collider Detector at Fermilab, in September, 1985, the interfaces between several components were opened and in two cases the splices appeared to be very marginal. Resoldering the splices allowed one of the sectors to go to higher currents, but the other remained unchanged.

Based on the experience gained in these tests, a number of low quench current magnets were replaced during the 1986 shutdown. Table 3 lists the reasons for replacement of all components changed since July 15, 1985. This period of time includes approximately eight months of operation, and twelve months of shutdown. The low quench current magnets represent one quarter of the total. There were five failures in operation which necessitated repairs; the remainder were replaced to improve the machine instrumentation and reliability. Again, there is some double-counting.

REASON FOR REPLACEMENT
83 COMPONENTS REPLACED SINCE JULY 15, 1985

Failure During Operation	5
Hipot Problems	9
Low Quench Current	20
Leak	28
Instrumentation	4
Damaged	3
Collider Experiment	2
Lattice Matching	8
Correction Element	4
Power Leads	3
Uncertainty	2
Total	88

TABLE 3

With the start-up following the long shutdown, each sector was again tested to identify the weak components, and it was determined that the Tevatron was able to run at 875 GeV. Two of the low quench magnets were replaced as the opportunity arose, and the machine energy was raised to 900 GeV. The Tevatron has been ramped to 920 GeV without quenching; one component has been identified which quenches when the Tevatron is stored at 920 GeV. Increasing the energy further by replacing magnets will be difficult. Every magnet in the Tevatron was measured at MTF; most of the low quench current magnets that were removed from the ring during the last shutdown have been remeasured. Two quench measurements are done; in one test, the "Quench Test", the magnet is simply

ramped at a given rate of rise until it quenches. In the "Saver Cycle" test, the magnet is ramped up and down, beginning with peak currents well below where it should quench; the peak energy is increased gradually until the magnet finally quenches. Figure 1 shows the results of the remeasurements on those dipoles which were recently removed from the Tevatron. Not shown in Figure 1 is one dipole which had decreased in quench current for the Saver Cycle test by more than 800 amps. (900 GeV corresponds to an excitation current of 3996 amps.) There has been an apparent increase in the quench currents on the average. This may be due to lower temperatures on the test stand for the more recent measurements. Another possibility is a marginal splice during the earlier measurements. Questions have also been raised about the accuracy of the current measurements during the Quench Test. With the one exception, there is no evidence for degradation due to ramping, quenching or repeated thermal cycling. The harmonic content was also remeasured, with good reproducibility except for the quadrupole component, which is strongly affected by the manner in which the large negative sextupole in the ends of the dipole is taken into account. There was a small change in the sextupole, which would arise from changes in the conductor placement. The angle of the dipole field changed by less than 0.5 mrad.

One problem that has developed is related to the hipot failures during the recent shutdown. It has been known for some time that the Kapton tape which is used for insulation, both for wrapping the beam tube during assembly and in the splices made during installation, loses its adhesive under cryogenic operation. The beam tube insulation has been unravelling, resulting in high voltage breakdown. This problem was fixed on the TC magnets during their repair. The possibility of an extended shutdown to fix the TB magnets has been discussed, and part procurement initiated, in the event that this develops into an operational problem. So far it does not seem to be; the hipots done at room temperature are more strenuous than those at liquid helium temperature, due to the insulating properties of the liquid helium.

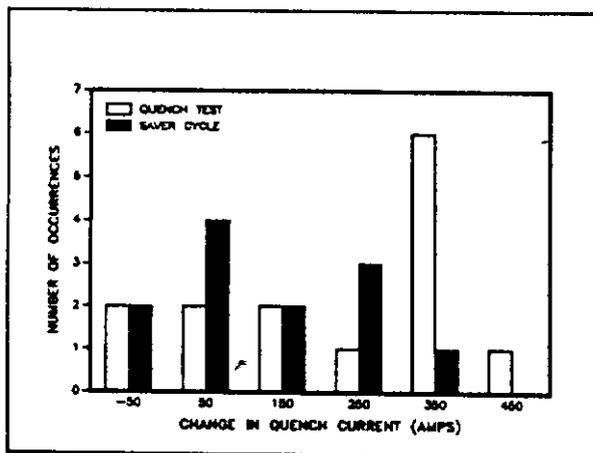


FIGURE 1
Change in Quench Current for Magnets Retested after Removal from Tevatron

Figure 2 shows the Saver Cycle quench currents for the 48 weakest magnets in the ring, based on the original MTF data, prior to the recent removal of the two magnets. Their positions have been indicated, along with the component which has been identified as being the weakest one remaining. There are clearly a few components in the Tevatron which exceed their MTF

measurements. Equally clear is that the spectrum is rising; many components would have to be replaced to gain another 25 GeV.

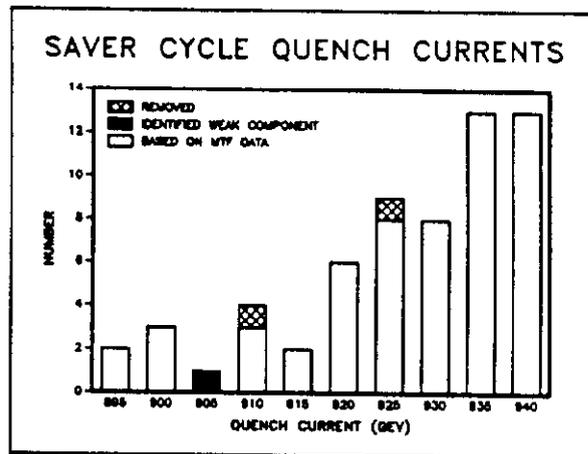


FIGURE 2
Quench Currents of the Weakest Magnets in the Tevatron

Quench Behavior

One obvious problem with a superconducting synchrotron is quenching. During the fixed target running periods, with the high intensity requirements of the many experiments, beam induced quenches are quite common. Quenches from all sources were the largest source of unscheduled downtime during 1985. Almost ninety percent of these quenches were due to beam loss. About half of the remainder were due to problems with the quench protection system; the subsystem which accounted for most of those, the heater firing units, have been rebuilt. More recently, during the present Collider run, quenches have been less frequent. Beam losses still account for seventy percent of the quenches, most of them associated with the beam injection or abort. Power lead problems, the second largest source, were responsible for ten percent. While the number of quenches divided by the number of days of operation is a number close to unity, that is not necessarily a good indicator. Injection quenches, for example, occur because some element is not working properly. There have been several instances in which four or five injection quenches happened in the span of a few hours until the problem was understood and corrected. The average number of quench episodes, where an episode refers to a single quench or a group of consecutive quenches caused by the same problem, is about four per week.

The refrigeration system for the Tevatron operates by monitoring temperatures and pressures throughout the system. When something is wrong, there is of course the danger of quenching. In the first fixed target runs, the response to bad refrigeration status was to turn off the ramp essentially instantly. This was inefficient, in that there was no opportunity for the system to recover, given the safety margin that exists, and the task of reestablishing the ramp is also time-consuming. With the beginning of Collider operation, the scarcity of antiprotons dictated another approach. Instead of turning off immediately, the Tevatron is allowed to continue through its cycle. In Collider operation, that could be indefinitely. In fixed target mode, it allows ramping to full field, extracting the protons, and ramping down. If the refrigeration status is still bad, the Tevatron stays at low field and beam is not injected again until the refrigeration has recovered.

This procedure has worked well, with very few quenches that could have been avoided.

Another problem encountered during the 800 GeV fixed target running period was heating of the safety leads due to repeated quenches in the same cell. Such quenches might happen while tuning up extraction, for example. The safety leads require about twelve hours to completely recover from a quench. There is a fair margin of safety, and quenches can occur more frequently on the average, depending upon the excitation current at the time of the quench. But if two high current quenches occurred within one or two hours, then the accelerator had to be left off until the leads cooled sufficiently. This problem was alleviated to some extent by the addition of vapor cooling to all of the safety leads in the ring during the recent shutdown. The vapor cooling helps in two ways. First, it modifies the temperature distribution so that the first quench is almost "free"; within a few minutes after the first quench, the peak temperature is the same as if there were no cooling and there had been no quench. Second, the cooling cuts the recovery time in half.

Downtime Statistics

The analysis of the downtime statistics for the Main Ring and Tevatron is complicated, and often misleading. Magnet changes in both machines are often not recorded as downtime, since that period of time is declared a "Maintenance and Development" (M&D) period. The typical time required for changing a Tevatron magnet is approximately five days if all goes smoothly. This includes two days to warm the string up to room temperature, two days of replacement and leak-checking, and another day to cool down. Main Ring magnet changes are much faster, of course. The length of time for a Tevatron magnet change has led to a dramatic change in the approach to M&D. In earlier years, shutting down every week was common. Presently, the weekly shutdowns have disappeared, with only short accesses for emergency repairs allowed. The machines are now operating essentially continuously, with no M&D shutdown scheduled until the end of the Collider run. If the necessity to replace a magnet arises, then the accumulated work can be done at that time.

Downtimes during operation typically reflect the complexity of the systems, and as such, the Tevatron downtimes are roughly twice the downtimes for the Main Ring. The majority of the Tevatron downtime during the present Collider run has been in quench recovery and cryogenics. The quench protection system, which was formerly a major contributor, has essentially disappeared from the downtime list.

Another way of examining the Tevatron Collider operation is to analyze the reasons for ending stores. In the first six weeks of this year, there were 24 successful proton-antiproton stores, that is, stores which accelerated particles to 900 GeV and turned on the low-beta. Of these, eight were ended deliberately (although the process of aborting the beam often resulted in quenches.) Of the remaining sixteen, one was related to the quench protection system, one to the cryogenics, and the remaining fourteen to all the other system which are part of any collider, superconducting or conventional. These include rf, correction elements, vacuum, power supplies, etc. Thus, only two ended for reasons that related to the fact that the Tevatron is a superconducting machine.

Summary

The Tevatron is now approaching the end of its fourth year. Those years have not been exactly trouble-free. While many problems have been solved, some remain. Measures have been taken to improve the reliability of the Tevatron on a number of fronts. The magnets themselves, as already discussed, have been "upgraded" by replacing suspect components. Improvements to the 13.8 kV system is underway, as are changes to add redundancy to the Central Helium Liquefier. The Tevatron is entering a period of essentially continuous operation, with no major interruptions presently scheduled.

In closing, the following table lists the fraction of the major component types which have been replaced at some point during these four years. As discussed earlier, only one-sixth of these were replaced because of failure during operation.

FRACTION OF COMPONENT TYPES REPLACED IN FOUR YEARS OF OPERATION

DIPOLES	12%
QUADRUPOLES	6%
SPOOL PIECES	16%
FEEDCANS	19%
ALL OTHERS	5%

TABLE 4

The complexity of the Tevatron magnets, and other components, has certainly influenced their reliability. The majority of the problems with the dipoles have been associated with the complexity of their ends. The warm-iron design, with its more rapid warm up and cool down times, has made these modest failure rates tolerable. It is hoped that the experiences at Fermilab, and this discussion of them, will be of benefit to the designers of future superconducting synchrotron magnets.

Acknowledgements

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