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TEVATRON Operational Experiences*

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ABSTRACT

Fermilabs superconducting accelerator, the Tevatron has been operational for nearly six years. The history of its operation is presented. Several long shutdowns for superconducting dipole repairs are discussed. The dominant factor influencing the repair was conductor motion which fatigued the cable in the magnet ends. Borescoping and x-raying techniques were used to determine which magnet ends required repair.

Detailed downtime logs were kept for each of the running periods. A discussion of the sources of downtime and a comparison for different operating modes is presented.

INTRODUCTION

Fermilab is a National Laboratory which provides the tools necessary to support and perform high energy physics experiments. The tools are in the form of proton accelerators. In the early 1980's a superconducting accelerator, the Tevatron, was built as an upgrade to the original 500 GeV accelerator. The Tevatron was designed at twice the energy (1TeV), yet offered a reduction in operating costs over the 500 GeV conventional magnet accelerator. Magnet development was the principal concern of this project from 1972 to 1979. [1] Then, from its near-final design in the late 1970's the Tevatron required considerable research and development in the areas of large scale superconducting magnet production, large scale helium refrigeration and transport, vacuum technology, quench protection and controls systems. To date, it is the highest energy proton accelerator in the world.

The Tevatron is a 2 km diameter synchrotron consisting of nearly 1300 cryogenic components as shown in Table 1. Its primary components are the dipoles, quadrupoles and spool pieces [1]. The 6.3m bending

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dipoles utilize a NbTi alloy superconductor to achieve 4.4 Tesla. Spool pieces house a variety of components. These include; correction magnets, quench stopper, vacuum barrier, relief valves, and thermometry. Every other spool piece contains safety leads which bypasses current around a quenched cell of magnets.

Table I. Tevatron Components

Dipoles	777
Quadrupoles	224
Spool Pieces	201
Feedcans	24
Turnaround boxes	30
Bypasses	21
Other	17
	1294

Refrigeration for the Tevatron is supplied by a hybrid system consisting of a Central Helium Liquefier (CHL) connected to 24 satellite refrigerators by a 7 km LHe, LN_2 transfer line [2]. This system provides redundancy by relying more heavily on one system should a problem develop in the other. Also, large inventories of liquid helium stored at the CHL dewar system are available for fast magnet quench recovery or cooldown following magnet repair.

The quench protection scheme for the Tevatron is an active system; it requires prompt detection of a quench and active components to remove the current from the quenching magnets [3]. The microprocessor based controls for the quench protection, refrigeration, vacuum, and correction element systems communicate to a main control room through a high speed link [4]. This allows for centralized operations, alarming, and data logging of all systems. The main control room is manned around the clock, 365 days a year.

Since its initial commissioning in 1983, nearly six years of Tevatron operational experience has been realized. An outline of the operational history of the Tevatron is presented. Modes of operations as well as major shutdown projects are described. Over the past six years, a detailed operational downtime log has been kept. Trends of downtime are considered, both as a function of time as well as mode of operation.

OPERATION HISTORY

Figure 1 shows the operational history of Tevatron over the past six years with our projection to the end of calendar year 1989. Details of the experiences for the years 1983-1986 have already been covered by Martin [5] and will not be repeated here. Details will be confined to 1987-1989.

The first colliding beam physics run opened 1987. Counterrotating 900 GeV proton and antiprotons were collided for a center of mass energy of 1.8 TeV. The run lasted fourteen weeks and was interrupted once for a Tevatron dipole change. Broken conductor strands, due to motion, reduced the current carrying capability of the dipole, resulting in the magnet change.

Year	Months	Event
1983	J F M	Last Tevatron Magnet Installed
	A	E & F Sector Tests (with beam)
	M J	Tevatron Commissioning
	J A S	Accelerated and Extracted 512 GeV Beam, 700 GeV Storage
	O N D J	400 GeV Fixed Target Physics
1984	F	800 GeV Extraction and Storage Tests
	M A M J	800 GeV Fixed Target Physics
	J A S O N	Shutdown for TC Dipole Repair, DO Overpass Construction and Antiproton Source Construction
	D	Accelerator Startup
1985	J F M A M	800 GeV Fixed Target Physics
	J J	800 GeV HEP + Pbar Source Commissioning
	A S O	Collider Test Run
	N D	
1986	J F M A M J J	Shutdown for BO Overpass and DO Experimental Hall Construction
	A S O N D	Accelerator Startup

FIG. 1. Tevatron Operational History

Year	Month	Activity
	J	900 GeV Collider Physics
	F	
	M	
	A	
1	M	Switchover to Fixed Target Physics
9	J	800 GeV Fixed Target Physics
8	J	
7	A	
	S	
	O	
	N	
	D	
	J	
	F	
	M	Shutdown for Dipole Repair, DO Overpass, and BO Shielding
	A	
1	M	
9	J	Accelerator Startup
8	J	900 GeV Collider Physics
8	A	
	S	
	O	
	N	
	D	
	J	
	F	
	M	
	A	
1	M	
9	J	
8	J	Studies
9	A	Shutdown for Dipole Repair
	S	
	O	
	N	
	D	

FIG. 1. Tevatron Operational History (cont)

Following the collider run there was a two week shutdown necessary to switchover to fixed target physics. During this time the colliding detector was moved from the collision hall to the assembly hall for maintenance and upgrade. Extensive maintenance of the accelerator systems also took place during this time. This included the replacement of five Tevatron components; three for suspected vacuum leaks, one for a low quench threshold, and one for power lead upgrade. Extensive maintenance to the cryogenic system was also accomplished including reciprocating expansion engine overhauls and system repurification at 80K. During the system repurification, we experienced a sitewide power outage. Fortunately, this had little impact on this mode of refrigeration system operation.

June of 1987 marked the return of 800 GeV fixed target physics. Although the run would last for 35 weeks, it proved to be interrupted by seven shutdowns for magnet changes and two sitewide power outages. Despite the interruptions, beam was delivered to the experiments at a higher rate than the 1985 run due to efforts to improve the beam intensity.

In March 1988 a three month shutdown began. Four major categories of work was scheduled for this shutdown, including: Upgrade of the main ring overpass at DØ, shielding of the main ring beam pipe from the BØ collider detector, repair of Tevatron dipoles in a quarter of the accelerator, and general system maintenance.

The rash of dipole problems during the fixed target operation prompted the dipole repair program. Prior to the shutdown, methods for inspecting the dipole ends were developed. Two methods, borescoping and x-ray were chosen for determining the extent of repairs that would be necessary. X-raying could be done while the magnets were warm or cold. Borescoping could only be done on warm magnets. Access for borescoping at one end was through a relief port, while the other end required disconnecting the liquid helium between magnets.

Four problem areas were being inspected at each end of a dipole.

<u>Leads</u>

> Leads were inspected for ties to prevent lead flexing during ramping. The preferred tie is Kevlar string, however some magnets used nylon ties. During repair, several magnets were found to have broken strands in the cable, the worst proved to have 12 of the 23 strands broken. Strand breakage may have been aggravated by low serial number magnets not having the G-10 conductor holddown block tumbled, to eliminate sharp edges.

<u>Bore tube insulation</u>

> The bore tube is insulated from the inside of the coil by spiral wrapped Kapton tape. At cryogenic temperatures the tape looses its ability to stick. This allows the tape to unravel at the upstream end of the magnet if it is not tied.

<u>Coil Clearance</u>

> Inadequate clearance between the end of the coil and the single-phase terminating plate can result in contact during ramping. Repeated force on the end plate has resulted in a cracked weld

on several dipoles, leaking helium to the vacuum space. Clearances were particularly a problem when round head screws were used instead of flat head on a G-10 lead holddown block. In several cases, screws were found to be backing out of the block. Clearances greater than 1.5 mm are adequate to avoid contact.

Bolted Conductor Clamp

As the leads leave dipole, they are held by an L-shaped G-10 block. In low serial number dipoles the block halves were bolted together. Over time and thermal cycles, several bolted connections have become loose or separated altogether. This was later changed to a riveted connection. Magnets with bolted blocks were repaired.

During the inspection and repair, a black greasy material was found in several dipoles near the refrigerator feed point. It was found to have a high lithium content, such as the grease used on the refrigerator expansion engines. No grease has been found at the bottom of the expander cylinder. It is suspected that grease migrates down the cylinder to the point where it freezes. The reciprocating motion then grinds up the grease. It then travels with the helium stream where it drops out at the first sudden expansion and the first dipole.

Inspection of magnets began in areas of the ring with low serial number magnets (A-sector). Although areas of the ring with the lowest serial numbers tended to require more repairs, serial numbers alone were not definitive. In all, six sections were fully inspected and repaired (A1, 2, 3, 4, B1, E1) and one was partially repaired (E3). Table 2 shows the results of the dipole repair as reported by Hanna [6].

Table II. Tevatron Dipole Repair

	Dipole Type			
	TB Dipole		TC Dipole	
	Up	Down	Up	Down
Ends Considered	104	104	96	96
Repair Reason				
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 block clearance	21	29	21	25
Beam tube Kapton	48	0	0	0
Inspection Type				
X-rayed	104	103	94	95
Bore scoped	104	84	8	78

In June 1988 the system started for a second 900 GeV collider physics run. It is expected that we will continue this run until July 1989. At that time we will warmup the entire system to room temperature in order to inspect and repair the remaining two-thirds of the Tevatron dipoles.

Tevatron Downtime

Prior to discussing Tevatron downtime, it is important to understand several fundamental differences in the fixed target and collider operational modes. During fixed target physics, protons are injected, ramped to full field, "spilled" to the experimental areas, the magnets are ramped down, and the cycle repeats. The cycling of the magnets means that the refrigeration systems must satisfy both the static heat load of the magnets as well as AC losses within the collared coils (predominantly hysterisis). Injecting and extracting proton on each cycle (57 seconds) also increases the odds for stray beam to cause a quench.

During collider physics, magnets are ramped to full field and remain there for many hours. This significantly reduces the refrigeration load by "eliminating" AC losses but increases the liquefier load necessary for vapor cooled power leads. Liquefier loads tend to not be seen by the satellite refrigerators, only by the central liquefier. Since protons and antiprotons are injected or removed infrequently, beam induced quenches tend to be less frequent.

Downtime in the following charts have been converted to weekly average for direct comparisons of four different runs: 1985, 800 GeV fixed target, 1987, 900 GeV collider, 1987, 800 GeV fixed target and 1988, 900 GeV collider run (through January 31, 1989). Detailed downtime logs have been kept for these runs. However, it should be noted that the method used can result in hours being counted more than once. For instance, if a quench is caused by an injection kicker misfiring downtime will be logged under injection supplies and under quench.

Figures 2, 3, 4, and 5 show the weekly average downtime for ten Tevatron subsystems for the 1985 fixed target, 1987 fixed target, 1987 collider (through January 31, 1989) and 1988 collider runs, respectively. Comparing the two fixed target run (Fig. 2 and 3) shows an order of magnitude increase in downtime due to the recent TeV magnet problems. Fatiguing cable strands and welds as mentioned in the previous section were the cause.

The more recent fixed target run resulted in fewer magnet quenches, yet resulted in more downtime as shown in Figure 6. Longer quench recovery times in the '87 run were primarily due to two factors. First, more full field beam induced quenches (as opposed to injection quenches) occurred due to higher beam intensities and fast beam spill to the experimental areas. Secondly, long system recoveries in the A1 magnet strings resulted from an intermittent ground fault. The problem cleared several hours after the quench making it difficult to isolate. During magnet replacements elsewhere in the ring, components in the affected electrical cell of A1 were charged out. After two replacement episodes involving seven components, a dipole was removed which proved to have lead insulation damage.

In comparing the recent fixed target run with the collider run (Figures 3, 4, 5, and 6), two major differences in downtime are evident. First, the continual cycling of the magnets in fixed target mode emphasized the fatigue problems previously mentioned. This resulted in a factor of thirty higher downtime due to magnet replacement. Second, Figure 6 shows 40% more downtime due to magnet quenching in fixed target mode. This is due to the continual transport of beam in and out of the Tevatron increasing the likelyhood of stray beam inducing a quench. Figure 6 also shows similar recovery times for the '87 runs, since both runs were dominated (80%) by full field quenches.

During the 1988 collider run, improvements in beam transport and proton-antiproton store durations resulted in a factor of two fewer quenches than in the previous collider run. However, quench recovery times were a factor of two higher. This was due to a large number of multiple house quenches. There had been an intermittent problem with beam kicker magnets prefirings which forces the particle beams to hit magnets in various locations around the ring. The intensity of the beam is such tat quenches in four different magnet strings was not uncommon.

Figure 5 shows a high amount of downtime for Tevatron magnets during the current collider run. This represents the time necessary to replace dipoles on two separate occasions as well time required to access the Tevatron tunnel to clean the correction element power leads. Over the years, a black conductive substance has formed on the leads, causing occasional leakage current to ground. The leads have been cleaned and coated with a nonconductive sealer.

Improvements in downtime for the cryogenic, power supplies, and quench protection systems were realized between the '85 and '87 fixed target runs due to upgrade and hardening of components. Cryogenic systems were most influenced by three improvements. They include: The addition of a liquid helium pump at CHL to supply inventory from the dewar system to the satellite refrigerators during peak ring usage or CHL outages, improvements in satellite expander mean time between failures, and the addition of controls software which helped monitor and debug the system.

Each satellite refrigerator has one reciprocating expander operating during normal modes of operation. To date, over a million expander hours have been experienced at Fermilab. Mean time between failures have increased to over 6000 hours. Durations between overhauls of over a year (8760 hours) have been realized, with the longest registering in at over 13,000 hours.

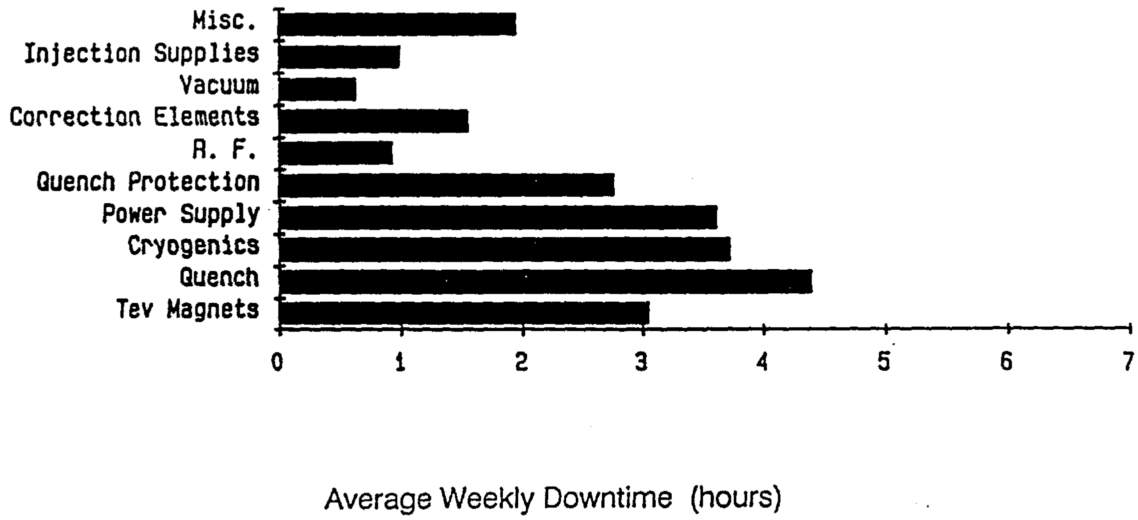

FIG. 2. Downtime for 1985 Fixed Target Run

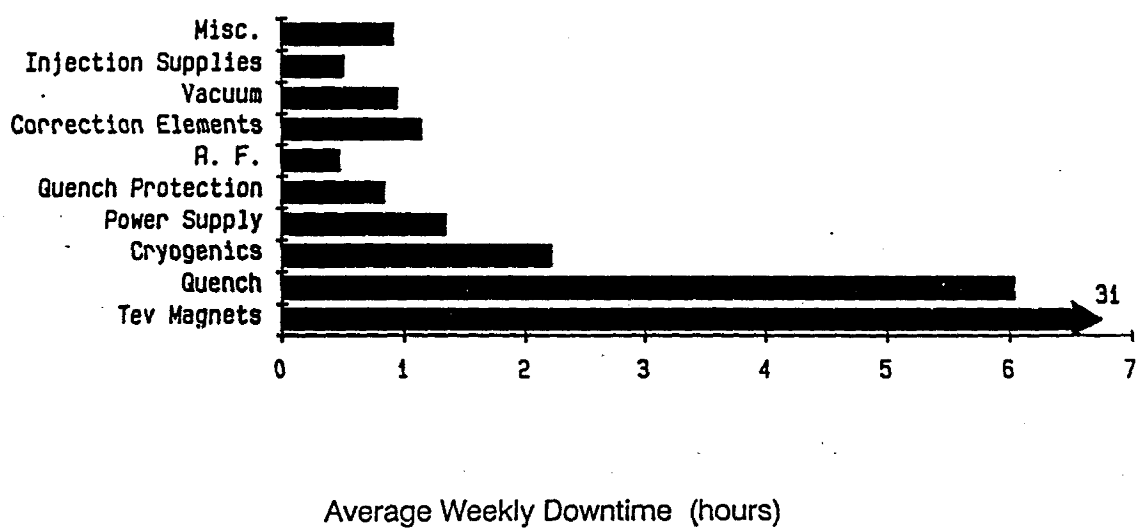

FIG. 3. Downtime for 1987 Fixed Target Run

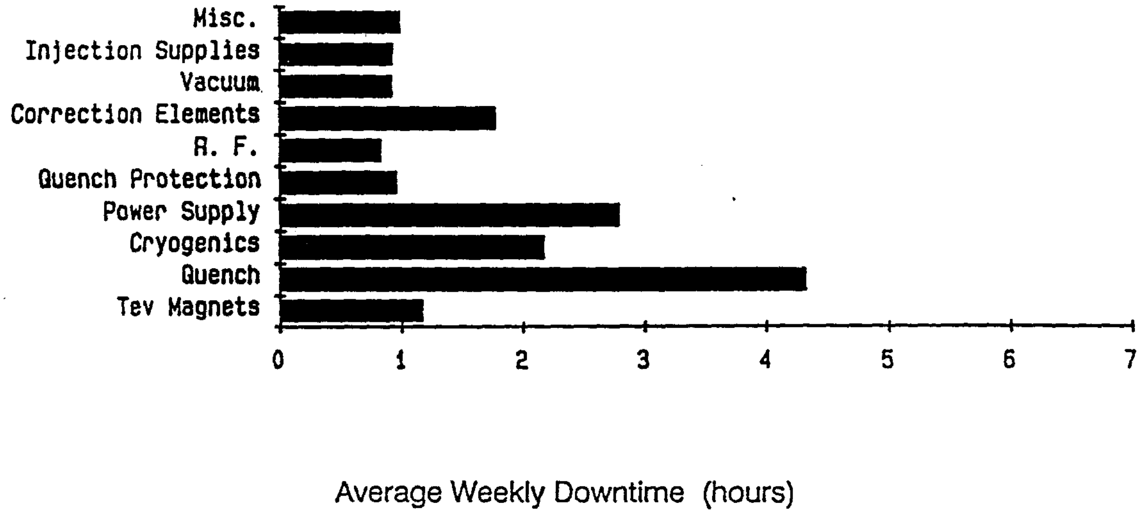

FIG. 4. Downtime for 1987 Collider Run

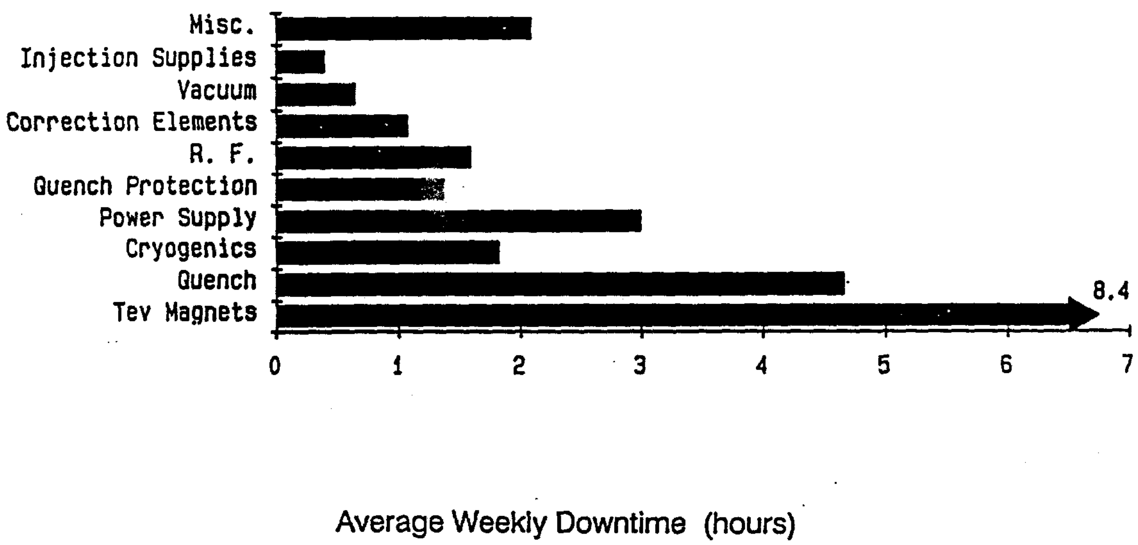

FIG. 5. Downtime for 1988 Collider Run (though January 31, 1989)

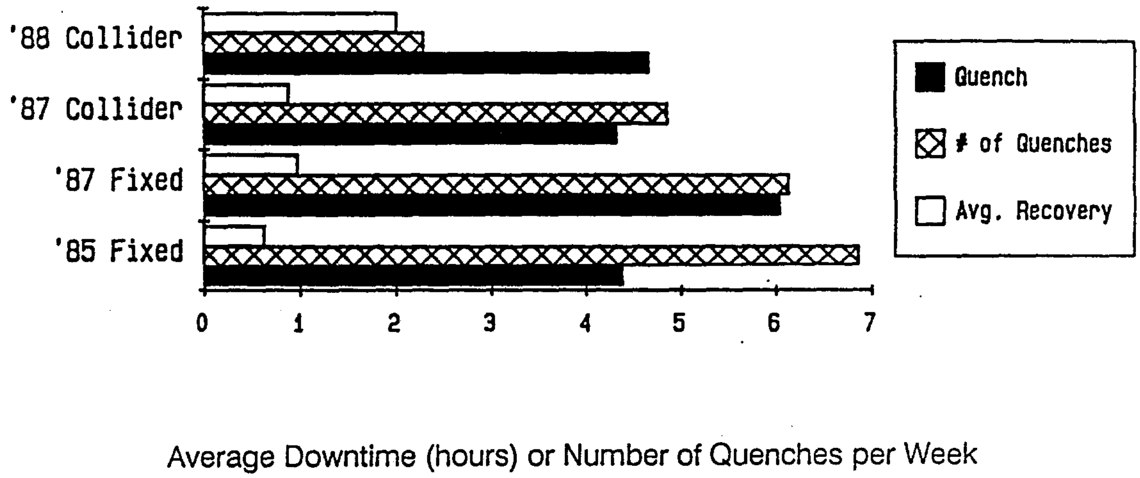

FIG. 6. Magnet Quench Downtime vs Operating Mode

SUMMARY

The Tevatron has just completed its sixth year of operation. This paper in conjunction with Martin [5] discussed the operational experiences throughout the six years. Magnet problems have been addressed during two long shutdown periods. Approximately one third of the dipoles have been repaired to date; mostly in areas with early production dipoles and areas prone to injection and extraction beam induced quenches.

The warm iron magnets of the Tevatron allow for a more rapid warmup and cooldown for magnet charges during operation. During a magnet change, one twenty fourth of the ring must be warmed to room temperature. To date there have been 110 such warmups, including two full ring magnet warmups. Fast cooldown following a magnet change is accomplished directly with a liquid helium cooldown wave. There have been no known problems directly associated with using this abrupt cooldown wave.

Problems associated with the Tevatron magnets have predominantly been in magnet ends. Typically, magnet end design takes a back seat to the coil design, as it should. However, it's importance is accentuated by the fact that it is the point at which "field" electrical and piping connections and thermal contraction takes place. The incorporation of magnet tests and life cycle tests can help find such problems earlier in a systems design or production.

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