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CURRENT OPERATING EXPERIENCE AND UPGRADE PLANS OF THE TEVATRON CRYOGENIC SYSTEM

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ABSTRACT

Fermilabs superconducting accelerator, the Tevatron has been operational for over six years. The Tevatron is a proton/antiproton collider used in high energy physics research. The cryogenic system is a hybrid design, consisting of a 4000 liter/hour central helium liquefier and twenty four 1 kw satellite refrigerators. Operating experience of the cryogenic system is discussed, including a historical perspective, accelerator systems downtime comparison, and specific hardware experiences.

Upgrade plans for the cryogenic systems includes improvements in reliability and in accelerator performance. To improve long term reliability, a second central helium liquefier with a 35% higher capacity is being constructed for operation in 1990. Plans to increase the operating energy of the accelerator to 1 TeV include the use of twenty four cold vapor compressors to lower the operating temperature of the magnets.

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 (1 TeV), 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. Its primary components are the dipoles, quadrupoles and spool pieces [1]. The 6.3m bending dipoles utilize a NbTi alloy superconductor to achieve 4.4 Tesla. Spool pieces house a variety of components.

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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.

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.

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. Current upgrade projects in the Cryogenic System are presented.

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 accelerator experiences have already been covered by Martin [3] and Norris [4] and will not be repeated here.

The entire system was cooled down for the first time in May 1983. Since that time, there have been six distinct physics runs, shown in Table I. Two modes of operation are used, namely fixed target and colliding beam physics. 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 conductor hysteresis). Injecting and extracting protons 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.

The first 400 GeV fixed target physics run was a continuation of experiments started using the 400 GeV conventional magnet accelerator. It wasn't until the 800 GeV run of 1984 that the higher energy of the superconducting Tevatron was exploited.

Table I. Tevatron Physics Runs

1983/84	400 GeV Fixed Target Physics	- 19 weeks
1984	800 GeV Fixed Target Physics	- 15 weeks
1985	800 GeV Fixed Target Physics	- 32 weeks
1987	900 GeV Colliding Beam Physics	- 14 weeks
1987/88	800 GeV Fixed Target Physics	- 37 weeks
1988/89	900 GeV Colliding Beam Physics	- 49 weeks

Both colliding beam physics runs utilized 900 GeV protons and antiprotons for a center of mass energy of 1.8 TeV. The higher energy operation in collider mode is possible due to the "elimination" of the AC losses. Upgrade plans are underway to allow 900 GeV and 1 TeV operation for fixed target and colliding beam physics, respectively.

The entire cryogenic system has been warmed to room temperature during three major shutdowns. The first was in the summer of 1984 to make a repair on 25% of the superconducting dipole ends. In Oct. 1985, the system was again warmed due to two major civil construction projects. The third warmup took place in July 1989 to again repair dipole ends[5]. This time all ends are being inspected by borescoping and x-raying to look for any of the following problems:

- Insufficient conductor tie downs
- Unraveling beam tube insulation
- Insufficient coil clearance
- Unscrewing conductor clamps

We expect to have to repair approximately 50% of the dipole ends. Following the magnet repair, the system will be purified and cooled down (Nov. and Dec. 1989) in preparation of an 800 GeV Fixed Target run beginning Jan. 1990.

Mar 83	Last Tevatron Magnet Installed
Apr - May 83	E & F Sector Tests (with beam)
May 83 - Jun 83	Tevatron Commissioning
Jun - Sept 83	Accelerated and Extracted 512 GeV Beam, 700 GeV Storage
Oct 83 - Jan 84	400 GeV Fixed Target Physics
Feb 84	800 GeV Extraction and Storage Tests
Mar - Jun 84	800 GeV Fixed Target Physics
Jul - Nov 84	Shutdown for TC Dipole Repair, DØ Overpass Construction and Antiproton Source Construction
Dec 84	Accelerator Startup
Jan - May 85	800 GeV Fixed Target Physics
Jul 85	800 GeV HEP + Pbar Source Commissioning
Aug - Oct 85	Collider Test Run
Nov 85 - Jul 86	Shutdown for BØ Overpass and DØ Experimental Hall Construction
Aug - Dec 86	Accelerator Startup
Jan - Apr 87	900 GeV Collider Physics
May 87	Switchover to Fixed Target Physics
Jun 87 - Feb 88	800 GeV Fixed Target Physics
Mar - May 88	Shutdown for Dipole Repair, DØ Overpass, and BØ Shielding
Jun 88	Accelerator Startup
Jul 88 - May 89	900 GeV Collider Physics
Jun 89	Studies
Jul - Nov 89	Shutdown for Dipole Repair
Dec 89	Accelerator Startup

Fig. 1. Tevatron operational history

TEVATRON DOWNTIME

Downtime in Figure 2 has been converted to weekly average for direct comparisons of five different runs: 1984 800 GeV fixed target, 1985 800 GeV fixed target, 1987 900 GeV collider, 1987 800 GeV fixed target and 1988 900 GeV collider run. 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 a magnet failure, downtime will be logged under TeV magnets and under quench.

CHL

Figure 2 shows a considerable reduction in downtime due to the central Helium Liquefier (CHL) between the first two fixed target runs and the remaining three runs. The 1987 collider run had no downtime associated with the CHL. This improvement is credited to three major improvements; the addition of a third redundant compressor, reduction in contamination, and the addition of a liquid helium pump.

In the earlier runs, contamination was a problem for CHL and the satellite refrigerators, particularly for prolonged runs. CHL was plagued with aluminum oxide dust, a product of the exchanger manufacturing process plugging a turbine inlet filter. The exchanger was eventually cleaned out with a high velocity flow and the problem has not reocurred.

The 1985 run was interrupted when the CHL coldbox became plugged with water. A small leak from a compressor water cooling jacket to a low pressure cylinder was the source. The system was modified to provide positive isolation between the water and helium.

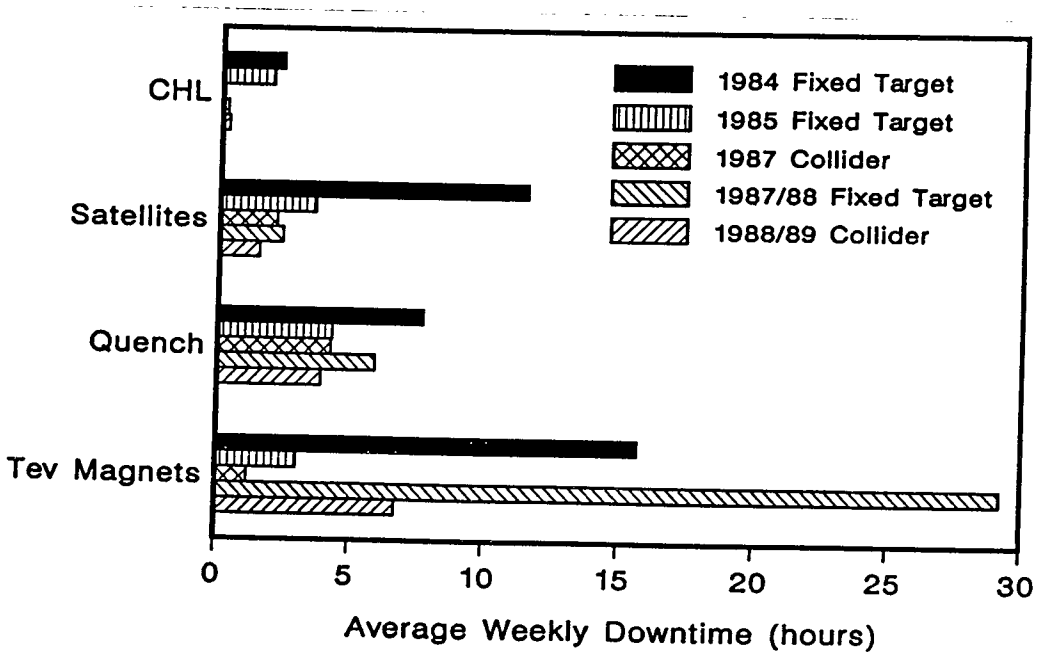

Fig. 2. System downtime by run

Nitrogen (air) contamination was also the source of several exchanger derimes. Better gas analysis equipment, operating procedures, and maintenance procedures have nearly eliminated this problem, even on one year runs.

The reliability of the plant and the performance of the whole cryogenic system has been greatly improved by having a reliable liquid helium pump. In the event of a coldbox or compressor trip, the liquid helium pump can maintain sufficient flow to the ring from a 64,000 liter liquid helium storage system while the third compressor is put on line or the coldbox restarted. Furthermore, the continuous operation of the pump has resulted in more stable refrigeration and a larger peak demand capacity being supplied to the ring. This is particularly important in fixed target operation with the swing in heat load due to AC losses in the magnets. This results in fewer ring trips and quicker recovery from magnet quenches.

Satellite

Figure 2 also shows a significant improvement in the satellite downtime between the 1984 and 1985 fixed target runs. This resulted from improvements in gas contamination prevention, expander lifetime and the CHL liquid helium pump. Nitrogen (air) contamination plating on satellite heat exchangers tends to result in a larger demand on CHL. Temperature excursions, such as a quench, could shift the contamination to form a restriction in the exchanger or freeze out on expander valve. Improvements in gas analysis equipment, purification procedures and maintenance procedures have nearly eliminated this problem.

At the end of the 1988/89 collider run we experienced significant pressure drop in the 300-80K heat exchangers at three adjacent satellite refrigerators. The problem was isolated to a leaking oil to water heat exchanger used to cool a satellite screw compressor. Upon investigation, we found that two-thirds of the 34 screw compressors have heat exchangers with dissimilar tube and tube sheet materials. Corrosion resulted, eventually causing leaks in the 8-10 year old exchangers. New exchanger cores are being manufactured and installed during our current shutdown.

Expander lifetime has also helped improve satellite downtime. Each satellite has one reciprocating expansion engine operating during normal modes of operation. To date, over a million expander hours have been experienced at Fermilab. Improvements in material selection and alignment has resulted in a mean time between failure of over 8300 hours during the 1988/89 collider run. Typically, we overhaul all expanders between physics runs, however, on one occasion we allowed an expander to go through two physics runs (13,000 hours) without failure.

During recent Tevatron magnet repair, we found a greasy material in the ends of magnets, mostly in the vicinity of the refrigerator feed point. Samples that were analyzed proved it to be expander grease. Evidently the grease migrated down the piston, freezes, and grinds into relatively fine particles. These particles freely travel with the liquid helium, dropping out of the flow at sudden expansions into cavities at the ends of the magnets. No evidence of grease was found at the bottom of the expander piston. Filters will be added in the exhaust U-tubes of the expanders during the current shutdown.

The third major source of improvement to satellite downtime was the addition of the CHL liquid helium pump. During fixed target operation, AC heat load represents about 30% of the total refrigeration requirements. If the ramping is stopped, the magnets cool down slightly due to the elimina-

tion of the AC losses. This slight change in helium density looks like a liquefier load to the satellite refrigerator. Satellite controls is such that the burden for liquefier loads is put on the CHL. Although this oscillation only lasts for 15 minutes, its demand is greater that the CHL capacity. The addition of the liquid pump allowed stored liquid to increase the facilities instantaneous capacity. As a result, the accelerator is able to resume ramping during any point in the oscillation.

Quench

A detailed representation of the Tevatron magnet quench statistics is shown in Figure 3. This figure shows the average weekly downtime, number of quenches and average quench recovery time for each of the five physics runs. It can be seen that number of quenches that occur in collider mode is less than in fixed target physics. This is due to the continual transport of beam in and out of the Tevatron in fixed target mode, increasing the likelihood of stray beam inducing a quench.

Quench recovery times tend to be longer for collider mode. In collider mode, beam induced quenches tend to be at high energy and often times in multiple locations. During fixed target mode, many of the quenches are at injection energy and thus recovery quickly.

Tevatron Magnets

The constant cycling (every 57 seconds) of magnets in fixed target mode is evident in Figure 2 by the downtime due to magnet failures. The problem during the 1984 run was limited to conductor fatigue at one end of half the dipoles due to inadequate tie-downs. Once repaired, the following fixed target and collider runs were considerably improved. During the 1987/88 fixed target run, fatiguing resurfaced. Consequently, all magnet ends are being inspected as mentioned earlier.

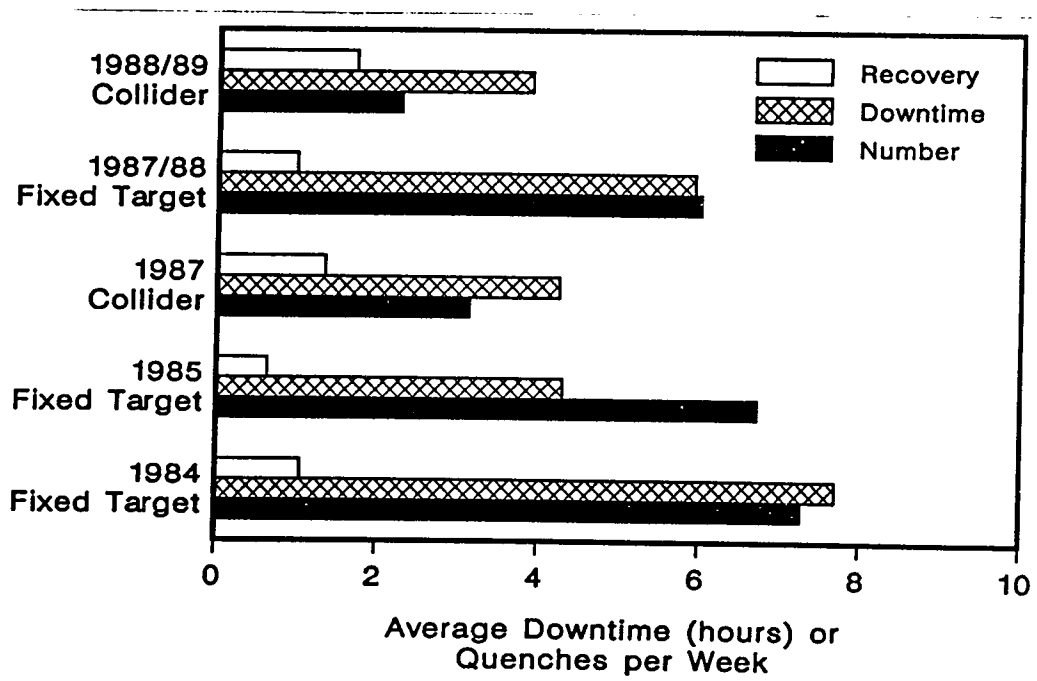

Fig. 3. Tevatron magnet quench statistics

System Upgrade

Two significant cryogenic upgrade projects are currently underway. The first, construction of a second CHL, addresses the question of reliability. The second, lower temperature operation, will allow higher energy operation in the Tevatron.

The Tevatron cryogenic system was designed with redundancy in mind. The magnets could be operated without the CHL, relying strictly on the satellites; or with CHL using less LN_2 and only one expander in the satellite. Unfortunately, the loads have been increased in several specialized locations beyond the capacity of the satellites. As a result, CHL operation is required to operate the Tevatron.

In order to regain our redundancy, a second CHL is being constructed for operation in 1990. Larger variable nozzle turbines will be used to achieve about 35% more capacity while retaining turndown capabilities. The higher capacity will be used in three ways; to defer maintenance on satellites experiencing equipment problems, higher consumption due to the addition of vapor cooled power leads for a new proton-antiproton beam squeezing system, and the higher wattage requirement of the lower temperature system described below.

A project is underway to increase the operating energy of the Tevatron through lower magnet temperature operation. The goal is to raise the operating energy from 800 to 900 GeV in fixed target and from 900 to 1000 GeV in collider physics. Design calculations, including computer simulation studies, established that cold vapor compressors with a subatmospheric intake pressure are required to accomplish this goal. Operation with a cold compressor in each satellite refrigerator will require the higher capacity second CHL.

Individual cold compressors have been tested for there suitability to the Tevatron operation [6]. During the recent collider run, four cold compressors were installed in the F-sector of the Tevatron. Approximately 1500 hours have been logged on each unit. Two study periods allowed us to investigate the magnet performance in F-sector (1/6 of the Tevatron) at three different temperatures. A peak energy of 1021 GeV was achieved with a subcooler pressure of 90 kPa (0.9 atm). Magnet performance for another sector of the Tevatron will be investigated prior to the next fixed target run. The goal is to have an operational system prior to the collider run in late 1992.

SUMMARY

The cryogenic system has performed well over the six year operation of the Tevatron superconducting accelerator. Constant improvements are being made to further reduce system downtime. System long-term reliability is being addressed through the construction of a second CHL. Future challenges include the reliable operation of the system for lower temperature operation in the 1990's.

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