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THE TEVATRON CRYOGENIC SYSTEM: Five Years of Operation, Lessons for Future Superconducting High Energy Accelerators

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Abstract The liquid helium temperature cryogenic system for the Fermilab Tevatron is the largest operating system in the world both from the standpoint of capacity and physical size. This system first brought into operation in 1983 has operated almost continuously for five years. Emphasis has been on achieving reliabilities associated with electrical power systems. During the present Tevatron collider run cryogenic reliability contributed to a maximum duration of 52.6 hrs. for the longest proton - antiproton collision run and efficiency of 82% in achieving the scheduled hours for collisions.

Reliability has been accomplished by incorporation of redundancy in critical components and buffering the output of devices so that downstream of a system no impact is observed even when a component has failed. That is the failed component such as a pump can be repaired or replaced prior to any change in the output of that system.

Other lessons that will help in future designs will be discussed.

A major development is a sector test (1/6 of Tevatron Ring) operated with four cold compressors in order to lower the temperature of the Tevatron in order to increase the maximum energy of the accelerator to 1 TeV. Test results should be available for presentation.

The Fermilab Tevatron's helium refrigeration system is one of the world's largest. It is a hybrid system and contains a large helium liquefier, a nitrogen reliquefier, a distribution system around the six kilometer circumference ring for liquid helium and nitrogen, pipes for room temperature high and low pressure gases, and 24 equally spaced satellite refrigerator systems. Individual satellites have the task of cooling, filling and maintaining at 4.5K their portion of the accelerator. These components can provide a total of 24 kw of cooling at 4.7K for the magnets as well as 600 liter/hour of liquid helium for power lead cooling and 1000 liter/hour of nitrogen for the magnet heat shields.

The large helium liquefier can supply over 4500 liter/hour of liquid and uses 3.6 MW of power. It consists of two 2000 hp, three-stage compressors that operate at 12 atm and supply 1200 gm/sec of helium gas to the "cold box". Three Sulzer turbine oil lubricated expanders are utilized in the CHL cycle. About 0.6 liters of liquid nitrogen is required per liter of helium produced.

* Operated by Universities Research Association, Inc., under contract with the U.S. Department of Energy.

Three 6000 m pipes have been installed in order to provide for helium distribution and collection. The room temperature 20 atm header is a 3 in. diameter stainless steel pipe and the collection header is 8 in. diameter stainless steel pipe. The most important part of the distribution system consists of the liquid helium transfer line. This line, which connects the output of the Central Liquefier to the 24 satellites around the ring, consists of 25 ~250m sections interconnected by vacuum jacketed U-tubes and is configured to form a complete loop. Each section consists of a 4.5 cm i.d. supercritical helium line and a subcooled liquid nitrogen shield. An expansion joint is provided at the center of each section for thermal contraction. One advantage of the loop feed is that in the case of failure of one section all 24 satellites can continue to operate by feeding part of the loop in a reverse direction. The transfer line can distribute 5000 liter/hour of helium and 3000 liter/hour of nitrogen. Estimated heat leak for the total line is very small: of the order of 3.6 kw at nitrogen temperature and 240 watts at helium temperature.

Helium is vented through valves into the header from the magnets only during cooldown or during a quench. Safety valves are mounted on every magnet. Nitrogen from the magnet shield is returned to the nitrogen reliquefier.

In principal no large quantities of helium or nitrogen should be vented into the tunnel except under extreme quench conditions or from the rupture of a magnet cryostat. Safety procedures do not allow personnel in the tunnel when the magnets are excited. Personnel entering the tunnel are required to carry oxygen monitors and breathing devices that can be used if the oxygen level becomes depleted.

Figure 1 shows the schematic of a satellite refrigerator with its associated magnet string. The high pressure (~20 atm) helium gas is supplied by 24 two-stage 350 hp Mycom oil-lubricated screw compressors located in six buildings around the ring. Therefore each satellite refrigerator normally has available ~53 g/sec of 20 atm gas which enters the satellite heat exchanger through manual valve MV101H. After passing down the heat exchanger system the gas enters the reciprocating wet expansion engine and is expanded to 1.8 atm. This cold flow is joined by low temperature helium from the Central Liquefier transfer line system. This Central Liquefier feed flows through electric valve EVLH and the two streams merge at point (13). After passing through subcoolers, the cryogen enters the upstream magnet string at point (14) and the downstream magnet string at point (17).

Magnet string temperature indication is designated TRQ (2) through (9). These carbon resistor thermometers are located at each quadrupole; i.e., every 30 meters along the string. The upstream and downstream throttling valves are labeled EVUH and EVDH respectively. Fourteen control loops are indicated. The philosophy that has been adopted is that all 24 satellites must be controlled from a central control room where one or more consoles are used for monitoring and adjusting the refrigerators. It is interesting to note that during operations excellent results have been achieved for different operating modes, such as automatic cool-down, ramping of the superconducting magnet strings with a 4000 ampere ramp, storage of proton and antiproton beam at 900 GeV energy for as long as 52.6 hours and automatic recovery from localized quenches.

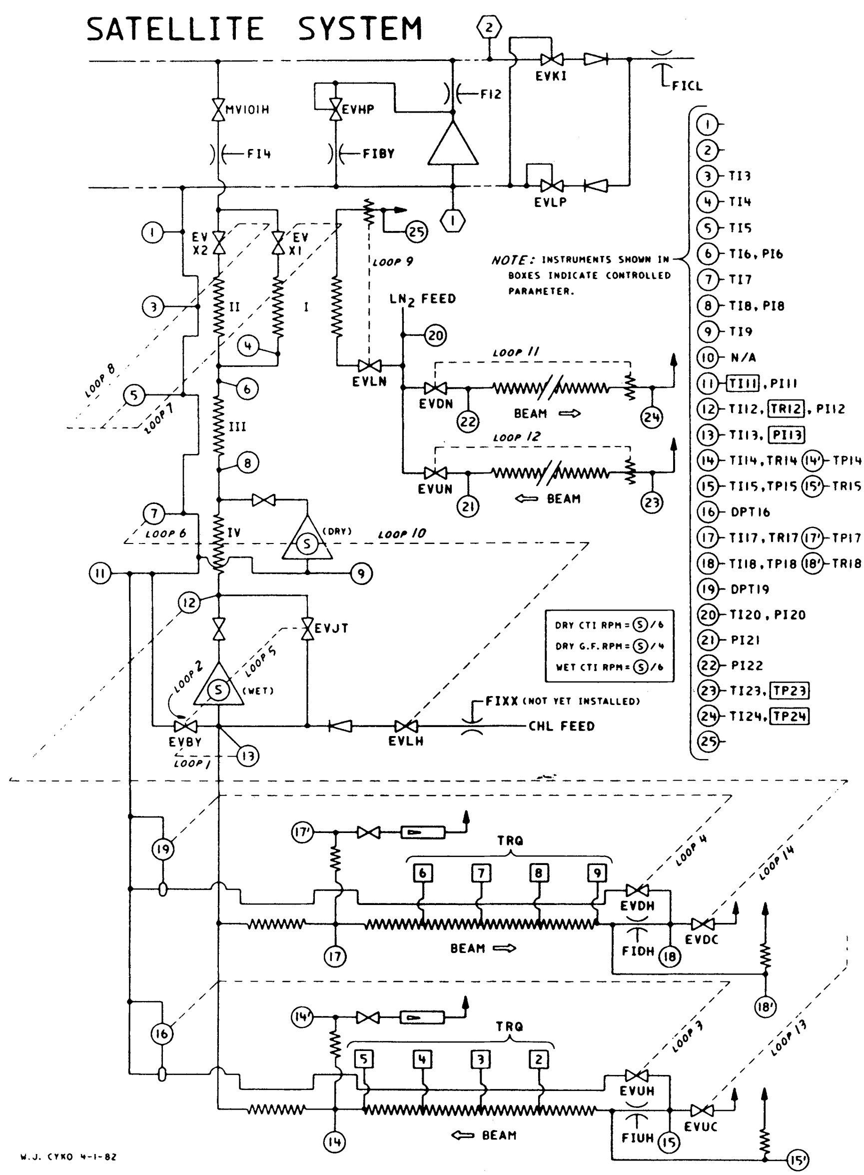

FIGURE 1. Schematic of satellite refrigerator and magnet string system.

The cooling loop concept for the Tevatron is shown in Figure 2. Simply, the pressurized single phase helium (points 14 and 17 upstream and downstream respectively) enters the first dipole and flows through the string until at the end a JT valve allows expansion of the fluid into the 2Ø return. Return pressure is ~5 psig and ~0.4K temperature variation exists along the string. About 10% liquid remains in the return stream just before entering the return side of the satellite.

Static heat leak measurements on magnet strings indicate 430 ± 60 watts (32 dipoles, 8 quads, and 8 spools). Ramping heat load is 270 watts for a 60 sec cycle. Measured static leak load at 4.7K is ~9.5 watts per dipole.

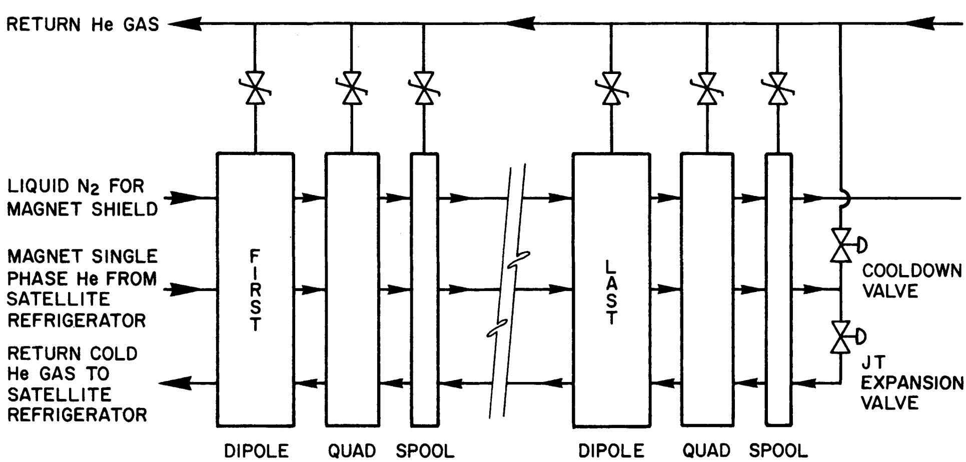

FIGURE 2. Cooling loop concept for Tevatron magnet strings.

J.D. Fuerst reported on cold compressor tests at Fermilab at a recently held cryogenic engineering conference at U.C.L.A. in Los Angeles. Figure 3 shows the modifications that were incorporated in four satellite refrigerators in order to carry out the test. CC indicates the position of the cold compressors which were of two varieties. In two cases a reciprocating CCI cold compressor was used and in two cases, a Creare turbine type cold compressor was used. New dewars were added at each satellite configured as shown in the schematic. This was primarily done in order to insure that 2Ø helium would not enter the suction of the cold compressors. For the test the intake pressure to the cold compressors were 1.04 atm and pressure ratios of ~1.3 gave 275 ± 15 rpm for the CCI units and 50,000 ± 7000 rpm for the Creare's when 50 g/sec was being pumped.

Results reported by Fuerst are seen in Figure 4 which are viewed as consistent with the expected performance of the Superconducting magnets if determined by the properties of the superconductor. The variation at 4.3K could be explained by training of magnets which had never seen this high a magnetic field before. Our conclusion is that Tevatron magnets can take advantage of lower operating temperatures provided by cold compressor operation and produce stronger magnetic fields thereby increasing the top energy of the accelerator.

When the initial operation of the Tevatron was reported it was said that 40% of the time the machine was scheduled for no operation occurred due to failures. Fifty percent of this downtime was directly associated with the Superconducting Accelerator. The major cause of this was due to three systems 1) cryogenics, 2) power supplies, 3) quench protection system and quenches. These three categories which accounted for 75% of the downtime was in the ratio of 2:1:1.

Cryogenic system downtime was divided into; 1) trips due to unstable operation or oscillations in the system that indicate the magnets may be too warm, 2) failures of expansion engines, 3) failure or reduced capacity of the central plant as a result of contamination, filter clogging, or inadequate supply of nitrogen or helium.

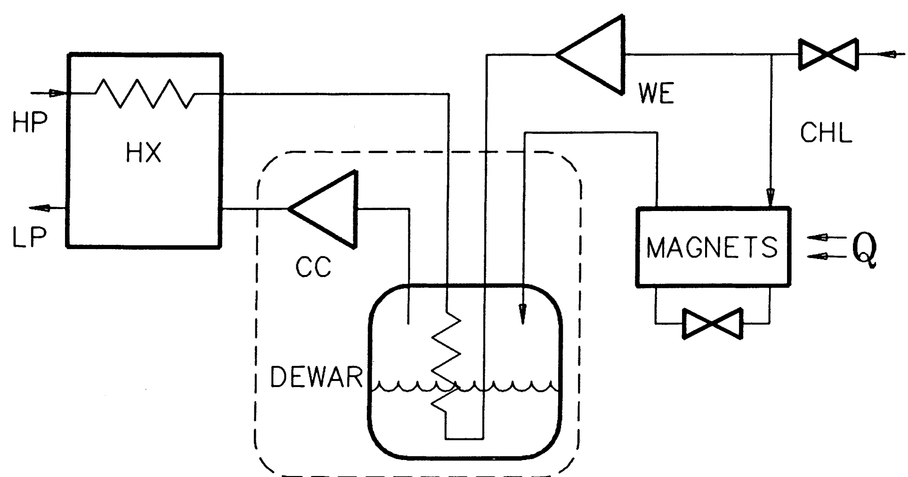

FIGURE 3. Satellite refrigerator schematic (with cold compressor and dewar).

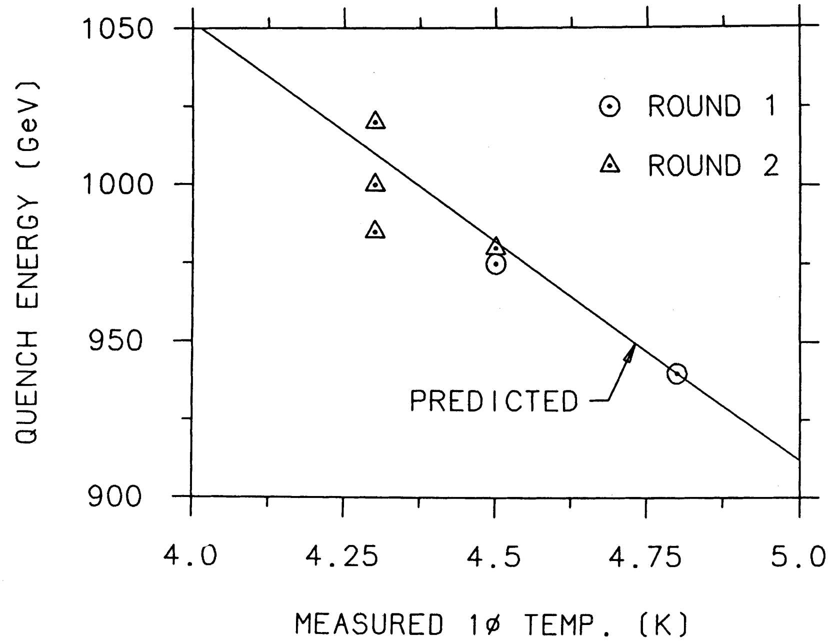

FIGURE 4. Quench performance vs. magnet temperatures.

Jay Theilacker reported on the current operating experience with the Tevatron Cryogenic System at the recent U.C.L.A Cryogenic Engineering Conference. Considerable reduction in downtime has been achieved as is shown in Figure 5 taken from Theilackers paper.

One of the obvious features of this figure is the almost zero downtime charged to the Central Helium Liquefier (CHL). This was the direct result of buffering features incorporated between 1985 and 1987. There was 16,000 gals. of liquid helium storage added with a liquid helium pump. When CHL trips (this can be due to expansion turbine overspeed or temporary electrical power failure) the liquid helium pump continues to supply liquid helium to the satellites from the storage dewars. It is then possible to return the cold box to normal operation. This procedure allows the accelerator to operate continuously through the upset period. Similar measures with the satellite system resulted in decreasing the cryogenic downtime to less than five hours per week.

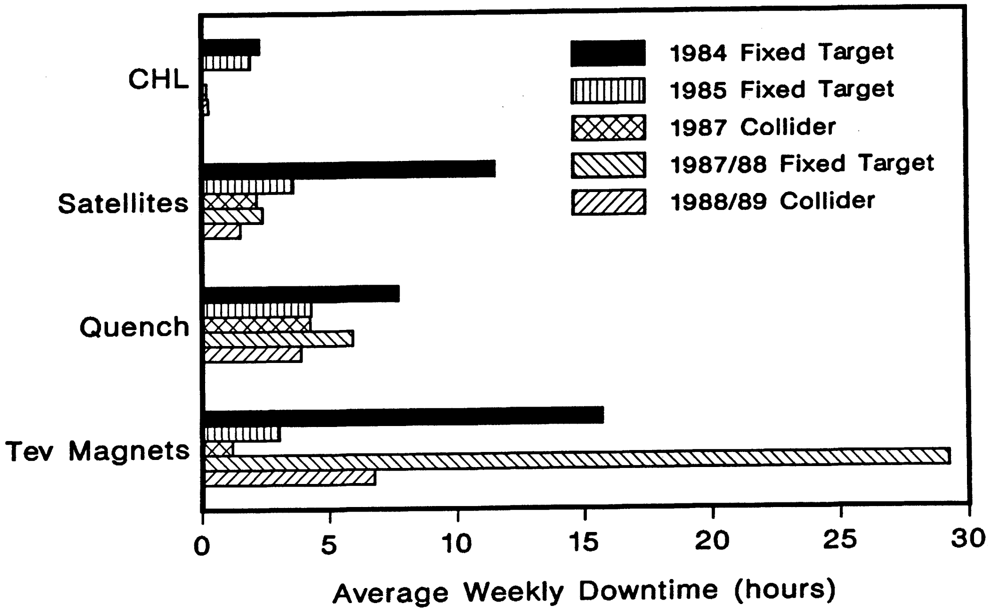

FIGURE 5. System downtime by run.

CONCLUSIONS

It has been demonstrated that the maximum field for long strings of superconducting accelerator magnet depends as expected on the operating temperature. For Tevatron magnets about 15 percent more magnetic field is available for a degree lower operating temperature. For future accelerators the refrigerator operating temperature should be cost optimized with the superconductor for the magnets or perhaps this potential reserve energy capability could be allocated to an improvement program.

While it is important to have sufficient refrigeration capacity for a superconducting accelerator it is prudent not to overdo the size. The penalty for capacity at liquid Helium temperature is ~330 watts at room temperature for every watt at 4.5K, therefore the helium refrigeration accounts for the majority of the electrical power used by the Accelerator Collider complex. It is not reasonable to turn off the refrigerator for maintenance periods due to the lengthy warm-up and cool-down cycles so the refrigeration runs essentially all the time. Fortunately Accelerators come in modules so what is required is measurements of refrigerator capacity on final components prior to finalization of refrigerator size.

Reliability is of the utmost importance. This is achieved by adequate redundancy i.e. components, such as filters and purifiers that collect contaminants and develop limiting pressure drops are dual so that the spare unit is brought on-line while the plugged component is regenerated. Similarly if a liquid helium pump is used an already connected spare pump can be valved into the system with minimum upset. Buffering is also important. By this we mean if a coldbox trip occurs sufficient liquid capacity is available to supply refrigeration until the cold box can be brought back on-line.