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Tevatron Lower Temperature Operation

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Overview

This year saw the completion of three accelerator improvement projects (AIP) and two capital equipment projects pertaining to the Tevatron cryogenic system. The projects result in the ability to operate the Tevatron at lower temperature, and thus higher energy. Each project improves a subsystem by expanding capabilities (refrigerator controls), ensuring reliability (valve box, subatmospheric hardware, and compressor D), or enhancing performance (cold compressors and coldbox II).

In January of 1994, the Tevatron operated at an energy of 975 GeV for the first time. This was the culmination of many years of R&D, power testing in a sector (one sixth) of the Tevatron, and final system installation during the summer of 1993. Although this is a modest increase in energy, the discovery potential for the Top quark is considerably improved.

Fermilab's superconducting Tevatron accelerator has reached its tenth anniversary of operation since being commissioned in 1983. Over the years, the Tevatron has operated at an energy of 800 GeV for Fixed Target and 900 GeV for Collider physics. The magnets limited the Tevatron to these energies for two reasons. First, the quality of the superconductor used in the earlier magnets was lower. Second, the operating temperature of the superconducting coils is higher than design. The higher operating temperature is due to heat leak not intercepted by the two-phase helium and higher than anticipated pressure drop in the two-phase helium circuit.

The operating energy of the Tevatron is defined by the ability of the superconducting cable to carry the necessary current density in the presence of high magnetic fields; the so-called cable short sample limit. The 1000 magnets in the ring form an ensemble with a distribution of quench currents with a full width of ± 60 GeV; the machine operating energy is determined by the lowest quench current of any magnet in the ring. There are two possible methods of increasing the machine energy: identifying and replacing the weak magnets with higher quench current elements, or lowering the temperature of the magnets that increases the critical current. Since the quench current of each magnet was measured prior to installation in the ring we can estimate that ~40% of the magnets would need replacement to reach 1000 GeV. Since weak magnets can only be identified and replaced serially this option is not viable, independent of financial considerations. We had therefore decided to implement lower temperature operation.

The present operating threshold of the Tevatron is 935 GeV with a peak coil temperature of 4.9K. In order to raise the energy of the Tevatron, the operating temperature of the superconducting coils needed to be reduced. The superconductor used in the Tevatron improves by 15% when the temperature is reduced by one degree Kelvin. Modifications to the cryogenic system were designed to achieve a maximum temperature reduction from 4.5K to 3.5K in the two-phase circuit of the Tevatron magnets. Sector testing in the Tevatron suggested that there would be a good chance that this would be sufficient to achieve higher energy without requiring magnet replacements. The ultimate limit of the cryogenic and power supply systems is 1100 GeV. Weak magnet identification and replacement will be necessary to achieve this level of operation.

Several major upgrades to the cryogenic system were required to reduce the temperature by up to 1K. Cold helium vapor compressors were procured to reduce the pressure, and thus the temperature, of the two-phase circuit of the magnets. Modifications had to be made to all external connections to the two-phase circuit in order to "harden" them for subatmospheric operation. Operation of cold compressors in a satellite refrigerator required a higher capacity Central Helium Liquefier (CHL). A second CHL was built (coldbox II) with larger expansion turbines in order to achieve a 35% capacity increase. The addition of cold compressors and associated instrumentation also required a major upgrade to the satellite refrigerator controls system.

The installation of the satellite refrigerator upgrades required the Tevatron to be warmed to room temperature for the third time in its history. Final commissioning of the coldbox II took place following the completion of Collider Run 1a in June 1993. The satellite refrigerator upgrades were commissioned beginning in October. A fourth compressor at CHL will be commissioned this winter, which regains redundancy for the higher capacity coldbox II. Long-term operational plans include optimizing the temperature profile throughout the Tevatron to minimize cryogenic power consumption, upgrade the original CHL for higher capacity, and to investigate taking the Tevatron to higher energies.

The American Society of Mechanical Engineers (ASME) designated the Fermilab Tevatron Cryogenic Cooling System as an International Historic Mechanical Engineering Landmark. Dignitaries from the ASME, Fermilab and DOE gathered at the Laboratory for an afternoon dedication on September 27, 1993. The ASME landmark designation recognizes the decade of reliable operation as well as the innovative engineering involved in the initial design and fabrication of the system. Many innovations included in Fermilab's system have served as a model for similar systems around the world.

Below is a chronological account of events associated with the commissioning of the cold compressors and the Tevatron higher energy power testing.

Cold Compressors

<u>Overview</u>

Lower temperature was achieved by pumping on the magnet two-phase helium circuit with cold vapor compressors. A subcooling dewar was located between the refrigerator and the magnet strings to buffer oscillations. The dewar is sized to help minimize the transients caused by the AC losses during ramp turn on/off in Fixed Target Physics.

Both reciprocating and centrifugal cold compressors can be made mechanically suitable for incorporation into Tevatron satellite refrigerators. One of the main driving forces for choosing a particular technology is based on a non-technical issue; physical space constraints in the satellite refrigerator building. A centrifugal cold compressor could be made into a U-tube, allowing it to be plugged directly into the valve box. As a result, no additional floor space was required. A contract was placed with Nissho Iwai American Corp. for twenty-seven centrifugal cold compressors in late 1991. The compressors were manufactured by Ishikawajima-Harima Heavy

Industries Co., Ltd. (IHI) of Tokyo Japan. Fermilab took delivery of all the compressors and their associated controllers in the fall of 1992 and commissioned in the Tevatron in December of 1993.

Installation

A cold compressor was installed at the A1 refrigerator during the 1993 shutdown for checkout and testing purposes. Installation went smoothly and the cold compressor operated as expected following installation. It was found, however, that after it was off for an extended period (a day or so), the compressor seized. This locked rotor condition was sensed by the high current draw and no evidence of pumping upon startup. The speed "readback" is actually based on the inverter frequency and not an actual shaft sensor and therefore gives misleading information under these conditions.

The compressor was changed out with a new one, with similar results. The compressor operated fine following installation but was seized after being off for a day or so. It was quickly determined that residual water vapor in the motor section of the cold compressor was cryopumping to the cold end. The motor normally has stagnant room temperature helium in it at the pressure of the compressor exhaust. Eventually, enough ice builds up in the close tolerance annular space between the warm and cold ends to freeze the shaft. It was found that in many cases, the locked rotor condition could be freed up by injecting warm helium gas at 40 psig into a fitting in the top of the motor housing. This small flow of warm helium eventually warmed the ice. Two negative side effects result from this however. First, the water is pushed deeper into the system. Second, the helium, must flow through the lower journal bearing, resulting in any bearing "dust" to be pushed down toward the impeller wheel.

Fortunately, we had not installed the majority of the cold compressors when the problem had been identified. We were able to institute a program of heating and vacuum pumping the motor housings to reduce residual water vapor prior to installation. Typically, eight cold compressors were piped together with two vacuum manifolds; one on the bayonets and one on the motor housing fitting. The motor housings were heated with a heat tape and carefully monitored to limit the case temperature to 150 F. Vacuum pumping continued until the motor housing achieved <15 μ at 140 F. This typically required 24 hours. The compressors were then cooled down, backfilled with clean helium and sealed with bayonet covers prior to installation.

This procedure worked well and greatly reduced the number of locked rotors after all twenty-four compressors were installed. We did however have a few lock up. The procedure was modified to vacuum pump down to <5μ at 140 F, which seems to have cured the problem.

B4 failure

Following the installation of all the cold compressors, we began testing groups of compressors to ensure proper operation. During this initial operation, one cold compressor (#4 at B4) made screeching noises on startup. This noise was not present during the ~2 hours of compressor acceptance testing on air in the shop. The compressor was removed with less than 1 hour of system operation and one of our three spare units was installed. We were quite concerned over this "failure" since we were now down to two spare units. The cold compressor was disassembled in our shop, the parts were photographed, and the rotor and impeller were returned to IHI for analysis and recommendations. The following observations were made at FNAL prior to sending the parts to IHI.

1. Both journal bearings were damaged. Some of the Teflon coating was blackened. Bare foil base metal was visible. The bearing was covered with a black powder which was analyzed to be burned Teflon.

2. The black Teflon powder was found on the back side of the impeller. One concern was that our purging warm gas into the motor housing to free the rotor pushed the bearing dust to the impeller. There was concern whether that amount of dust would have a detrimental effect on the rotor/impeller balance.
3. The thrust bearing looked normal.
4. The impeller had several gouges in the base metal, presumably from the balancing process at IHI.
5. The tips of the impeller vanes looked normal (i.e., no evidence of contact with the housing).
6. Dimensional measurements showed that the shaft was within tolerance.

Results of the analysis by IHI were received in the spring of 1994.

<u>Fall 1993 operation</u>

Little time was given for cold compressor commissioning during the fall of 1993 in order to expedite the Tevatron startup. A failure in a B1 low ß quadrupole component gave us the opportunity to perform cold compressor tests in a limited number of locations. We were limited to a few satellite refrigerators due to the desire to minimize the laboratories power consumption. The reserve capacity of the CHL Coldbox II with two compressor operation (instead of full capacity, three compressor operation) will allow operation of a few cold compressors at minimum speed and one compressor operating at low temperature.

We took the opportunity during the one week period to repair B1 to spin all the compressors and to test C3 at low temperature. The C3 system was operated with two-phase helium temperatures ranging from 4.45K down to 3.68K. The following observations were made.

1) The system, to first order, operated as expected.

2) After calibrating the magnet thermometry in place (using two-phase helium at ~1.1 bar), the expected increase in single-phase to two-phase temperature difference with lower temperature was measured. This is due to the decrease in helium specific heat. Note that the carbon resister thermometry used in the Tevatron single-phase was only calibrated down to 4.2K. We are extrapolating below that point.

3) After calibrating cold compressor pressure and temperature instrumentation in place (at ~1.1 bar), lower than expected cold compressor isentropic efficiencies were measured. The peak efficiency expected at the design conditions was 70%. Over the full range of operating conditions, the expected efficiency was greater than 60%. An efficiency of 60% was used in our system simulation in order to predict the overall system performance. The measured efficiency was between 40-50% and showed signs of being a function of the cold compressor inlet pressure.

4) In the course of measuring the cold compressor efficiencies, we found that our data acquisition system displayed crosstalk between A/D channels under specific conditions. An A/D channel read properly until the preceding channel went above 5 volts. At that point an offset proportional to voltage was added to the reading. We were careful to avoid this condition on subsequent efficiency measurements.

5) Large swings of inventory were experienced, as expected. Operationally, this is a bigger problem abruptly going from lower temperature to a warmer setting. Under this situation, stored refrigeration in the magnet helium inventory requires no refrigeration from the satellite as it warms to the new setting. This can last for 10s of minutes. Since it is not practical to shut off the satellite all together, this results in the dewar overfilling, which in return trips the

cold compressor on two-phase protection. The long term solution is to burn off the excess capacity with a heater in the dewar. Unfortunately, the heater electronics were not completed during the initial commissioning.

December 1993 operation

Tevatron higher energy commissioning tests took place in December of 1993 and January of 1994. During the December testing, the cold compressors proved to be very stable, but the efficiency of the units was low. The lower efficiency resulted in our not being able to lower the temperature of the Tevatron as much as we had planned. We were able to achieve stable operation at 3.93K two-phase temperature with the full capacity operation of Coldbox II.

After the testing, we found that the lower efficiency was due to a large pressure drop on the cold compressor inlet filter. This explained why the efficiency was a function of cold compressor inlet pressure. The filter was added after the fact due to a failure of our prototype unit. This unit was badly damaged when it was struck at high speed by a one centimeter long stainless steel chip. The chip was presumably left in the test cryostat during fabrication. It was decided that the filters were not necessary on the final system since the piping between the dewar and the cold compressor was minimal on the new valve boxes and the piping had been borescoped. On December 21, all of the cold compressors were removed from the Tevatron to have the filters removed.

January 1994 operation

Following the filter removal and dehydration process, the compressors were re-installed on January 5. Our procedures for installation or removal of cold compressors required that the liquid helium inventory be removed from the dewar and magnet systems. This meant that we had to transfer all of the Tevatron helium inventory to the liquid or gas storage systems and back again. We were able to accomplish this in a 24 hour period. Since then we have investigated the safety of removing or installing a cold compressor after removing the liquid inventory from the dewar, but leaving the inventory in the Tevatron magnets. This would considerably simplify the process.

We realized a 10-15% increase in cold compressor efficiency after the filters were removed. This allowed us to further lower the two-phase temperature of the Tevatron to 3.84 K and still remain within the capacity of Coldbox II. This brought the efficiency up to levels consistent (to within the accuracy of our measurement) with the prototype unit measurements.

We were optimistic about the system testing in January, having found and solved the efficiency problem. However, testing in January was plagued by cold compressors tripping off. This was a complete surprise, since the testing in December proved to be very reliable. The first problem found was due to the commissioning of the dewar heater systems. We did not have adequate time to tune the gains for the heater loops prior to Tevatron higher energy testing. It turned out that the initial gains were too high, resulting in violent boiling which spilled two-phase helium over into the cold compressor. This trips the cold compressor off due to an overcurrent situation. After discovering the problem, we disabled the heater control loops and began to run without them, as we did in December. We continued to have cold compressors tripping off and found that a controls problem was turning the heaters back on. Further adjustments to the control loop were necessary to ensure that the heater would not activate.

We were once again optimistic that we had solved the problem. Unfortunately, the compressor tripping continued. As before, the trip indication was current overload. We originally thought that the cold compressors were seeing two-phase caused by a heat transfer process "foaming" the liquid in the dewar. The speculation was that the filter was able to coalesce the liquid out of the stream during the December testing. It was later found that the problem could be cured by changing the controlling parameters of the cold compressor. It appears that the sensitivity to tripping increased following the filter removal.

Spring 1994 operation

During the spring of 1994, we operated five cold compressors during the Tevatron operation in order to investigate the tripping phenomena plaguing the January higher energy testing. We began by operating them at minimum speed, in order to keep the LHe requirements to within the capacity of Coldbox II operating with two compressors. We suspected that a changed in control loop parameters would help solve the problem. The result was that compressors were no longer tripping off. When we changed the parameters back to those used in January, the problem began reoccurring. The tripping was associated with how fast the compressor was allowed to accelerate. If the cold compressor accelerated too quickly, the result was a sudden drop in the compression ratio (near 1.0) and an increase in the current draw. The mechanism is still not well understood, but the solution (limiting the acceleration) is within an acceptable operating envelope.

We received a report back from IHI as to the cause of the failure in the B4 cold compressor. It turns out that a rotor which failed QA testing somehow made it back into the manufacturing queue. They did not state what phase of QA testing the rotor failed. The compressor is being repaired under warranty and will be final assembled at Fermilab with IHI personnel. We were relieved to hear what the problem was, in that it gives us more confidence in the other units and to the number of spare complete units (three) and individual spare parts we keep on hand.

The journal and thrust bearings in the cold compressor are foil dynamic gas bearings. In order to achieve the appropriate level of gas dynamics, IHI imposes a 40,000 rpm minimum speed on the compressors. On startup, the shaft contacts the foil bearing. This contact is handled by a Teflon coating on the inner surface of the foil. This spring, IHI informed us of an improved bearing design which is more rugged and requires a lower minimum speed (20,000). Switching over to this new bearing design is appealing for two reasons. First, having a more durable bearing is always appealing, since it is virtually impossible to guarantee that the compressor won't see two-phase helium. Second, having a lower minimum speed will allow us to operate more cold compressors during periods when higher energy operation is not required and still be within the two compressor capacity of Coldbox II. This is critical in helping us understand the cold compressor operation and to gain experience and confidence in their operation.

Liquid level measurement in the subcooling dewar is critical for the reliable operation of the cold compressor systems. As a result, two devices were designed into the system; a removable superconducting liquid level probe and a differential pressure cell utilizing a warm transducer and cold to warm capillary tubes. The differential pressure transducer was used as the primary device in all satellites except one which had a plugged capillary line.

Studies at CEBAF showed that superconducting liquid level probes have two fundamental pressure/temperature regimes where they do not work properly. One of those regimes is below the minimum operating pressure/temperature of the Tevatron low temperature upgrade. The other is at elevated pressure, which becomes an issue during cooldown or following magnet quenches.

Besides the fundamental problem areas, we experienced several other problems which we have been systematically addressing. They include:

1) Finding the optimum current for our operational regime.
2) Proper cable routing and grounding to eliminate external noise.
3) Optimum rotation of the probe such that the irrigation holes in the sheath are not pointing toward one of the two primary inlet spouts.

Work on the superconducting liquid level probe continues in the hope that it will be a reliable backup device, or become the primary control device.

Tevatron Higher Energy Power Testing

Magnet testing was performed on a system of four satellite refrigerators accounting for 1/6 of the Tevatron ring. To date, system tests have been made with prototype cold compressor equipment in F, A and B sectors of the Tevatron. The tests ran for about three months in F-sector (Spring 1989), one month in A-sector (Fall 1990/Spring 1991), and for one week in B-sector (Spring 1991). Six weak magnets have been identified (F28-5, F26-4, A48-3, A34-2, A28-4) and one has been replaced (F28-5). All of the magnets were in the bottom 20% for MTF Saver Ramp quench tests. Four of the six were in the bottom 10%. All of the magnets quench well into flattop (10 to 20 seconds) suggesting an I^2R heating problem or a delay time for AC peak heating to reach the high field portion of the magnet where the superconducting margin is smallest.

Tevatron higher energy commissioning tests took place in December of 1993 and January of 1994. A total of 17.5 shifts were dedicated toward commissioning the system. Of those shifts, 8 shifts where devoted to tuning or operational problems, while 9.5 shifts where devoted to Tevatron higher energy power testing.

During the December testing, the cold compressors proved to be very stable, but the efficiency of the units was low. The lower efficiency resulted in our not being able to lower the temperature of the Tevatron as much as we had planned. After the testing, we found that the lower efficiency was due to a large pressure drop on the cold compressor inlet filter.

Power testing in December took place in two blocks; December 2-4 and December 8. During the first block, time was spent tuning the system and gaining our first serious operational experience at lower temperature. The rest of that block was spent power testing the Tevatron. The principle observations from the testing are as follows:

1. Considerable magnet training took place. Following nine training quenches, the Tevatron quenched at 997 GeV @ 3.93 K two-phase temperature.
2. Nearly all the quenches were on the ramp up, as opposed to well into flattop during the A and F sector testing.
3. A lower quench current (2-3%) was realized in the Tevatron testing than during the A or F sector testing which was at the same or higher temperature.
4. After the training had settled down, quenches did not occur in isolated locations, but instead moved throughout the Tevatron.

The second block emphasized the power testing of the two low ß systems, followed by one Tevatron quench at slightly lower temperature. The principle observations from the testing are as follows:

1. The D0 low ß system achieved a 1000 GeV, $\beta^* = 0.25$ m squeeze without quenching.
2. The B0 low ß system quench at 963 GeV, $\beta^* = 0.25$ m squeeze.
3. The Tevatron was cooled slightly colder than the previous block of testing, but quenched at a lower current (987 GeV @ 3.84 K two-phase temperature).

On December 21, all of the cold compressors were removed from the Tevatron to have the filters removed.

Results of the sector testing, as well as Tevatron operation at normal and reduced temperatures are shown below. Considerably more magnet training was realized during the Tevatron commissioning than during the individual sector testing. The ultimate energy reached in the Tevatron was lower than what was expected for the temperature achieved. It is not known why the Tevatron quench behavior differed from the F and A sector testing.

Tevatron	935	GeV	@	4.50 K	two-phase temperature
F-sector	1021	GeV	@	4.08 K	two-phase temperature
A-sector	1034	GeV	@	3.93 K	two-phase temperature
Tevatron	997	GeV	@	3.93 K	two-phase temperature

Following the filter removal, the compressors were ready for re-installation on January 5, 1994. We realized a 10-15% increase in cold compressor efficiency after the filters were removed. This allowed us to further lower the two-phase temperature of the Tevatron to 3.84 K. As previously mentioned, the power testing on January 7 was plagued by cold compressors tripping off.

The Tevatron higher energy testing on January 7 was limited to concentrating on achieving successful higher energy "stores". This includes ramping up to an energy and sequencing the low ß quadrupole magnets used to achieve colliding beams. We successfully achieved a store at 975 GeV with a $ß^* = 0.25$ m for over an hour. Attempts to go higher resulted in a quench of the low ß magnets at 985 GeV. It is believed that the factor which will limit the operating energy of the Tevatron is the B0 low ß circuit, not the Tevatron dipoles.

Peak pressures in the single-phase during magnet quenches is always of concern. Previous work showed that peak pressure increased linearly with energy. If that trend continued, peak pressures at 1.1 TeV could reach 220 psig. Tests were performed in the Tevatron to measure peak pressures. The peak pressures rolled off at 900 GeV at 160 psig. It is speculated that the process is heat transfer limited.

Concluding Remarks

The current plan is to operate the Tevatron at 900 GeV through at least November, 1994. At that time, the issue of raising the energy of the Tevatron for collider operations may be reopened. Prior to using the system, full system testing time will be necessary for reliable higher energy operation. One month of Tevatron operation at low temperature while at 900 GeV will help to commission the system with a minimum impact on physics research.

In the mean time, we will continue to study subsystems operation as best we can, during collider operations. We currently have achieved 10,000 hours of cold compressor operating experience. Long-term reliability and fine tuning the system control algorithms remain outstanding issues.

Acknowledgments

Years of research and development were necessary to ensure that the Tevatron low temperature upgrade would result in a safe, reliable, and operable system. Only through the dedication of the Accelerator Division Cryogenics Department personnel could the system be installed and commissioned in the short time given.

The efforts of the AD Controls Department for the design and installation of the satellite refrigerator controls upgrade in greatly appreciated. Assistance by the AD EE Department and AD Main Accelerator Department during power testing is appreciated.