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Status Report on the Tevatron Lower Temperature Upgrade

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STATUS REPORT ON THE TEVATRON LOWER TEMPERATURE UPGRADE

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A cryogenic upgrade has been completed for Fermilab's Tevatron accelerator to lower the magnet temperature and increase the particle energy of the machine. Each satellite refrigerator uses a cold vapor compressor to pump on a subcooling dewar capable of lowering the magnet system's two-phase temperature to 3.56K. Larger wet expanders, subatmospheric modifications, and a new distributed control system were included in the design. A second Central Helium Liquefier with a 5400 liter/hour rated capacity was also brought on-line. Installation of the new lower temperature equipment and operating experiences during the Winter/Spring 1994 physics run including power tests are discussed.

INTRODUCTION

The original Tevatron Cryogenic System, commissioned in 1983, consisted of a 4000 liter/hour liquefier and 24 satellite refrigerators. Used in tandem, this hybrid system was able to boost the satellite capacity from 625 watts to 966 watts. The load for each satellite refrigerator consists of two, 125 meter long magnet strings. These magnet strings use subcooled helium which is counter heat exchanged with two-phase flow returned to the satellite refrigerator. This configuration results in two-phase temperatures of about 4.45K with a magnet coil temperature 10 to 400 mK higher.

During the summer and fall months of 1993, Fermilab upgraded the Tevatron cryogenic system by re-designing each satellite refrigerator so that the two-phase temperature of the superconducting magnet strings could be lowered to 3.56K. The need for lower temperatures was based on a desire to attain higher colliding beam energies. Fermilab has a short-term goal of increasing its beam energy from 900 GeV to 1000 GeV (4000 to 4444 amps). Given that the Tevatron's superconductor improves its current carrying capabilities by 15% per degree Kelvin, it was decided that lowering the operating temperature of the magnets was the appropriate solution for achieving these goals.

REVIEW OF SATELLITE MODIFICATIONS

The satellite modifications implemented were numerous and ranged from cryogenic hardware to controls. A description of modifications is presented here. Technical details for each portion of the upgrade were presented at the Cryogenic Engineering Conference in July 1993, in Albuquerque, N.M., USA.[1,2,3]

- Installed New Valve boxes
  Each valve box contains a 130 liter subcooling dewar and is used to connect the refrigerator to the superconducting magnets. The valve boxes are designed to accept the centrifugal cold compressor in a U-tube configuration.

- Installed Cold vapor compressors
  A centrifugal cold compressor was installed in each satellite. This machine is manufactured by Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) of Tokyo, Japan. The machine is a high speed, gas bearing turbomachine capable of operating from 40,000 to 95,000 rpm with flow rates varying from 40-70 g/s.

- Made Two-phase circuit leak tight
  The upgrade requires us to operate the two-phase circuit subatmospheric and therefore to avoid contamination problems it must be leak tight. This impacted 12 relief devices, 5 bayonet connections, 4 control valve stems, and 8 pressure measurements per satellite.

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- Converted Wet expanders to 7.5 cm diameter piston machines
  The effect of the newly designed cycle caused wet engine inlet to operate in 7K range (previously 5K). To achieve the same volumetric throughput we converted the machine into a 7.5 cm diameter piston device (previously 5 cm).

- Installed New 5.6 kW control package for 7.5 cm piston wet expander
  Upgrading the wet expanders to 7.5 cm piston machines required a 5.6kW motor control package. We are using an AC Variable Frequency Drive made by Mitsubishi. This setup includes a Regenerative Unit for continuous braking.

- Installed New Distributed Control System
  Every refrigerator and compressor building's distributed control package was upgraded to a Multibus-II platform and Intel's 32 bit, 80386 microprocessor. The control system, like the cryogenic system, is divided into 6 sectors with Token Ring used as the ringwide communication link.

INSTALLATION SCHEDULE AND INITIAL COOLDOWN

Fermilab ended Collider Physics Run 1A on June 1, 1993 and began warming up the Tevatron cryogenic system to 300K. During the 20 week period between June 1 and October 18, all the satellite refrigerator modifications were completed. Ringwide purification and cooldown to 80K began on October 18. Permission was granted to continue cooldown to 4.5K and on November 2 all wet and dry expanders were operating. The entire Tevatron was full of liquid again by November 9. Checkout of the power supply system and verification of past performance levels began shortly after.

At the end of August we installed a cold compressor into the A1 refrigerator. This was the first cooldown of a completely modified refrigerator. During these initial tests, the cold compressor had a seized rotor on the cold compressor after the machine had been off for a day or two. This problem surfaced again during ringwide turn on for power testing.[4]

Also after installing all cold compressors we attempted to verify correct operation of each on a warm system. One cold compressor, at the B4 refrigerator, made loud screeching noises. The machine was removed. Later IHI informed us that the cause was a bad rotor which had mistakenly been shipped to Fermilab.

During the months of October and November significant time and effort was taken to make the system performance reliable. Much attention was given to the new distributed controls system. Although throughout the installation process the majority of the hardware had been tested on 'warm' refrigerators, a vast amount of software had never been truly tested until the installation process was complete. With the Fermilab Controls group and Cryogenic Systems group working together, the controls began to become quite reliable towards the end of the November.

No significant problems were experienced with our valve boxes during initial cooldown. Other than the large manpower effort for resolving controls system problems the majority of our time was spent re-training ourselves to understand the performance characteristics of the new cryogenic system.

INITIAL COLD COMPRESSOR OPERATION AND POWER TESTING

Tevatron higher energy commissioning 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 were devoted to Tevatron higher energy power testing.

We began turning on all cold compressors December 2. Our goal was to pump down each magnet system to a two-phase temperature of 3.93K. This temperature was based on three items: 1) in theory we needed a 7.5% increase in energy to get to 1000 GeV (machine had been powered to 935 GeV); 2) previous sector tests had achieved 1000 GeV at this temperature or higher; 3) we needed to operate at a temperature that would not overburden the Central Helium Liquefier (lower temperature equals higher liquid usage). The initial ringwide turn on of the IHI machines was somewhat difficult. Eight of the twenty-four machines tripped on Inverter Overload within the first sixty seconds. This trip indicated that we had a Locked Rotor condition. We had seen this problem prior to the ringwide startup when we attempted to start units periodically. The problem seems to be a condensing of water vapor from the warm-end to the cold end which is able to solidify in such a way as to lock the rotor. Each rotor was freed by injecting 300K helium into the warm-end.

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 principal observations from the testing are as follows:

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

The second block of December testing emphasized the two Low Beta systems (special quadrupole magnets located at the B0 and D0 interaction areas), followed by one Tevatron quench at a slightly lower temperature. The principal observations from the testing are as follows:

- The D0 Low Beta system achieved 1000 GeV.
- The B0 Low Beta system quenched at 963 GeV.
- The Tevatron was cooled slightly colder than the previous block of testing, but quenched at a lower current (987 GeV with a 3.84K two-phase temperature).

On December 21, all the cold compressors were removed from the Tevatron to have inlet filters removed. These filters had a much higher pressure drop than originally believed and were causing low IHI efficiency and thus more burden on CHL. Following the filter removal, the compressors were re-installed on January 5, 1994. We realized a 10-15% increase in cold compressor efficiency after the filters were removed.

The testing on January 7 was limited to concentrating on achieving successful higher energy "stores." This included ramping up to an energy and sequencing the Low Beta quadrupole magnets used to achieve colliding beams. We successfully achieved a store at 975 GeV at a two-phase temperature of 3.84K for over an hour. Attempts to go higher resulted in a quench of the Low Beta magnets at 985 GeV. It is believed that the factor which will limit the operating energy of the Tevatron is the B0 Low Beta circuit, not the Tevatron dipoles. During this round of testing, however, we experienced two spontaneous cold compressor trips and seven trips immediately following quenches. During the December testing we had no trips. It appears that the sensitivity of the cold compressors to tripping had increased following the inlet filter removal.

We ended the power testing with a conclusion that we can power the Tevatron to 975 GeV with a 3.84K two-phase temperature. No further power testing has been completed.

SECOND CENTRAL HELIUM LIQUEFIER

The second Central Helium Liquefier (CHL)[5] has been operating since December 1993 for Collider Run 1B. High energy testing of the Tevatron was supported with three compressors in operation (180 g/s output). Since the completion of power testing, CHL has been operating with only two compressors (140 g/s output). Only during periods of high capacity needs, such as after cryogenic system operation difficulties (e.g. power outages/glitches or equipment failures) have three compressors been used. Turbine brake valve failures experienced during the early part of the run have been corrected by replacement with sturdier valve seats and stems. Turbine stability and performance has been acceptable and operator tuning of plant capacity with nozzle controls has been fairly easy. Turbine inlet filter contamination accumulation has not been a problem since the addition of a third stage of oil coalescing. Some contamination accumulation due to nitrogen introduced during an early plant system upset has been removed through a standard warmup and purification technique. A fourth compressor installation has been completed and awaiting final safety review determination. Operation of this compressor is anticipated for June 1994.

PRESENT TEVATRON AND COLD COMPRESSOR STATUS

After the January power testing, Fermilab decided to proceed with Collider Run 1B at 900 GeV with pursuit of higher energies possibly occurring later in 1994. This decision was based on physics issues and the reliability problems which had surfaced. Due to money constraints the lab decided not to operate CHL to the extent that would allow us to operate all the cold compressors. Since mid-January, with the Tevatron fully operational, we have been operating cold compressors five at a time in hopes of understanding the spontaneous and quench-induced trips.

After analyzing available motor speed, motor current, and pressure ratio data a possible solution to our quench-induced trips became evident. When we quench a magnet in the Tevatron, a large pressure rise occurs in our suction header which is common for all refrigerators. This pressure rise in turn elevates the discharge side of all the cold compressors (we turn off the cold compressor at the quenching house). The pressure rise occurs quickly and with a typical magnitude of 20-35 kPa. The cold compressor, operating via a dedicated PID loop, tries to maintain a constant intake pressure. We discovered that if we allow 5,000 rpm step changes at a frequency of 2 seconds we sometimes trip on overload. If we reduce the maximum step changes to 2,000 rpm and allow them only every 6 seconds the IHI performance does not seem to be worsened and we do not trip. We have now put a combined 10,000 hours on 20 total machines and experienced only 2 quench-induced trips. Both trips occurred near 50.7 KPa (0.5 atm). The spontaneous trips during power tests remain unexplained but acceleration-deceleration problems due to control loop tuning was probably also the cause. We have had no spontaneous trips since power testing.

RELIABILTY DATA FOR NEW EQUIPMENT

A concern in upgrading the refrigerator system was to maintain the same reliability we had in the past and hopefully improve upon it. The Accelerator Division keeps detailed data on failures which keep the machine non-operational. To analyze reliability statistics for the Low temperature modifications, statistics have been gathered for Run 1A (last pre-upgrade run) and for Run 1B (present run). This data is presented in Table 1.

TABLE 1. Comparison of Reliability Data for Run 1A and Run 1B

	Run 1A June 15, 1992-May 31, 1993		Run 1B Dec. 15, 1993 - May 31, 1994	
Category of Failure	% Of Cryogenic Downtime	Total # Of Hours Down	% Of Cryogenic Downtime	Total # Of Hours Down
Expanders (Mechanical)	18.80%	15.1	55.5%	40.0
Expanders (Electrical)	10.70%	8.6	0%	0
Kautzky Reliefs	35.70%	28.9	18.5%	13.4
Distributed Controls	6.90%	5.6	0%	0
Cryo Control/Electronic	1%	0.8	0%	0
Cold Compressors	NA	NA	0%	0
Instabilities	4.3%	3.4	26%	18.8
Power Lead	22.6%	18.3	0%	0
Total Cryo Downtime	NA	80.7	NA	72.2
Total Calendar Time	NA	8400.0	NA	3208.0

Our downtime since the upgrade has been dominated by wet expander failures; specifically, cyclic metal fatigue failures of the main crankshaft. We have had five such failures since cooling down in November. We believe we can reduce this failure rate by using higher strength steel and also surface treat the material.

It must be noted that we have not experienced any downtime related to new valve boxes, new distributed controls system, new expander controllers, or cold compressor operation during Run 1B.

FUTURE WORK

We are continuing to operate cold compressors a few at a time to gain more knowledge about their operating behavior. Work continues on perfecting instrumentation and control systems required to reliably operate this equipment. Run 1B is scheduled to continue until a shutdown in November 1994. It is our hope to continue our efforts in attaining reliable lower temperature operation at that time.

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