Fermi National Accelerator Laboratory

FERMILAB-Pub-93/374

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December 1993

To be published in *Advances in Cryogenic Engineering*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

UPGRADE OF THE TEVATRON CRYOGENIC SYSTEM

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ABSTRACT

Fermilabs superconducting Tevatron accelerator has reached its tenth year of operation. This year, three significant upgrades to the cryogenic system will become operational; a second central helium liquefier, a Tevatron satellite refrigerator lower temperature upgrade, and a satellite refrigerator controls system upgrade.

The decision to build a second central helium liquefier (CHL) was originally based on redundancy; protecting accelerator operation from a major CHL failure such as a heat exchanger. Higher capacity turbines were used in the second coldbox, which will result in an estimated 5400 liters per hour production rate. Preliminary commissioning of the coldbox took place in 1992. Full capacity testing will take place in 1993.

To aid in the discovery of the top quark, it is desirable to increase the particle energy in the Tevatron accelerator. The machine is limited to an energy of 900 GeV due to magnet conductor short sample current at the existing operating temperature. An upgrade is underway to lower the temperature of the accelerator ~1K. The short term goal is 1000 GeV operation with a 1100 GeV long term goal. Cold vapor compressors will be used in each of the 24 satellite refrigerators to achieve the temperature reduction.

An upgrade of the existing satellite refrigerator controls system is necessary to incorporate the added control devices, instrumentation, and controls algorithms required by the low temperature upgrade. The existing Z80 Multibus I based system will be replaced with a 386 Multibus II system. New features will be incorporated, including processor to processor communications, fast event driven circular buffer, hierarchical alarm system, higher level language support, and more elaborate controlling algorithms.

INTRODUCTION

The Tevatron Cryogenic System is a hybrid design; consisting of a 4000 liter per hour liquefier and twenty-four satellite refrigerators.[1,2] The hybrid design was incorporated for redundancy. If a satellite refrigerator was ailing, we can rely more heavily on the Central Helium Liquefier (CHL). Conversely if the CHL was ailing, we can rely more heavily on the satellite. Each satellite has a capacity of 625 watts in a standalone mode and 966 watts consuming liquid helium from CHL in satellite mode. The total system capacity at 4.5K is 27 kW. The hybrid design has proven to be beneficial for maintaining good reliability for a warm iron design superconducting accelerator such as the Tevatron.[3,4]

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The superconducting magnet coils are cooled by subcooled liquid helium that is continuously counter heat exchanged with two-phase flow. The advantage of a two-phase cooled system is the possibility for uniform temperature over a long distance. (Care must be taken to account, however for the preference of helium to stratify.) [5]
There are forty-eight 125m long magnet strings associated with the Tevatron. Typical operating temperature for the two-phase is 4.45K. The superconducting coils operate 10 to 400 mK higher due to heat leak and AC losses.

SECOND CENTRAL HELIUM LIQUEFIER

It became apparent early that the CHL was essential for Tevatron operations. There was always a concern that a large failure, such as a heat exchanger, would keep the Tevatron off for many weeks. As a result, plans were made to build a second redundant liquefier.[6]

Spare heat exchangers for Coldbox I were packaged into a second coldbox. The capacity of Coldbox I is limited by the turbine capacity and not heat exchangers. Therefore it was decided to buy larger turbines for Coldbox II to best match the heat exchanger and compressor configuration. It has been estimated that the final configuration will have 35% higher capacity (5400 liters per hour).

At the time the second coldbox was conceived, there wasn't a direct application for the increased capacity. As a result, variable nozzle turbines were purchased to allow efficient turndown of the plant to the nominal 4000 liter per hour. This would allow the plant to nominally operate at the 4000 liter per hour and then operate at full capacity during system cooldown or to liquefy gas from high pressure storage to the 20,000 or 44,000 liter storage dewars.

Coldbox I utilizes two large reciprocating compressor systems. For redundancy, a third compressor system was added shortly after the system was commissioned. The new Coldbox II will require three compressors for full capacity operation. As a result, a fourth compressor system is being installed to regain compressor redundancy. The reciprocating compressors inherently do not have efficient turndown capabilities. The fourth compressor is therefore being restaged in order to achieve 25% higher throughput. This will allow efficient operation of Coldbox II at 4000, 4350, or 5400 liters per hour corresponding to 2, 2.25, and 3 compressors, respectively.

The two coldboxes are not meant to operate at the same time. One is envisioned to be in a ready state, should a problem occur in the other. In order to keep them as separate as possible, redundent distribution systems, LHe pumps, controls system, and LHe heater were incorporated. The idea was to guard against events which could affect both coldboxes and thus render our redundancy ineffective.

Coldbox II has been commissioned to 5200 liters per hour. The capacity was below design values for two reaons. First, full compressor flow was not used due to the status of the satellite refrigerators at the time of commissioning. This resulted in about 6% less compressor flow to the coldbox. Second, there was inadequate time to tune the turbines for optimal efficiency. Both of these points will be pursued during the cryogenic system startup this fall.

LOWER TEMPERATURE SATELLITE REFRIGERATORS

It is desirable to increase the energy of the Tevatron from its current 900 GeV in colliding beam physics to 1000 GeV. The current carrying capability of the superconductor used in the Tevatron improves by 15% per degree Kelvin in the range of interest. As described earlier, the superconductor temperature is a function of the two-phase circuit temperature (and thus pressure). We had originally hoped to achieve 1000 GeV without going subatmospheric. It became clear that an unreasonable amount of magnet replacements would be required to accomplish this. Magnet replacement requires five days, and unfortunately only the weakest magnet per sector (there are six sectors) can be found at a time. Subsequently, the process can be very time consuming.

Since we knew we would have to operate subatmospheric, every effort was made to minimize the volume affected. This resulted in our choosing cold vapor compressors to pump on the magnet two-phase circuit. With positive pressure no longer being our constraint, we designed for even higher energy until other limits were reached. As it turns out, the natural limit is 1100 GeV. At that point, the power supplies, power leads, cryogenic system capacity, and possibly the magnet field quality all become limiting factors. It has been estimated that a 1K temperature reduction plus some amount of magnet replacements would be necessary to achieve 1100 GeV. This would require a two-phase operating pressure of 50.7 kPa (0.5 atm).

There are several configuration possibilities which could be made to the cycle when incorporating cold compressors. The affected components include the cold compressor, the satellite low temperature expander, a subcooling dewar and the LHe (from CHL) feed point. Simulations were performed to compare various cycles on an exergy basis.[7] The cycles were also subjectively compared for merits of operability (ability to isolate oscillations from the load, off design operation, and failure mode considerations).

The cycle chosen is shown in Figure 1. A 130 liter subcooling dewar was placed between the refrigerator and the load. This dewar serves two purposes. First it buffers refrigerator oscillations from the load. Second, it adds refrigeration capacitance to help compensate for short term peak loads caused during ramp turn off. (In fixed target physics operation, beam is injected, ramped to full energy and extracted over a 57 second cycle. There are considerable hysterisis losses in the superconductor while ramping. As a result, the steady state temperature of the helium while ramping is higher than when the ramp is off. When the ramp is turned off the helium cools down and mass is added to the magnet system. This looks like a large liquefier load to the satellite refrigerator and lasts for between 6 and 10 minutes.)

The way the cycle is configured, the heat of compression in the cold compressor results in a larger consumption of LHe from CHL. This will require the operation of the higher capacity Coldbox II. As a result, we will lose our redundancy at CHL, except for short outages of Coldbox II in which case we can operate Coldbox I supplemented with the LHe pump from the storage dewar system.

Space limitations in the satellite refrigerator building forced us to "package" the subcooling dewar into a new valve box. The valve box connects the satellite refrigerator to the superconducting magnets, some 9m below. Since the valve boxes are connected directly to the magnet system, this forced us to thermally cycle the Tevatron to room temperature during installation. This will be the third time in ten years that the Tevatron has been thermally cycled to room temperature. The new valve boxes were designed in-house and manufactured by Ability Engineering Technology, Inc.

All two-phase to atmospheric connections are being "hardened" for reliable subatmospheric operation. There are considerable connections which are affected. For each of the twenty-four satellite refrigerators there are:

12	relief devices
5	bayonet connections
4	control valve stems
8	pressure measurements

Some of these connections are in the new valve box and could easily be designed accordingly. However, the majority required retrofit of existing equipment. The use of double seals with guard vacuum between was not practical for any of the devices. The devices incorporate either a double o-ring with guard helium or a copper gasket vacuum seal.

Several configurations of reciprocating and centrifugal cold compressors were tested over the years.[8,9,10] During our testing it became clear that we could not guarantee the cold compressor would not see two-phase helium under upset conditions. This made the reciprocating compressors, particularly the Cryogenic Consultants Inc. design which could reliably operate subatmospheric, an attractive option. However, space constraints in the satellite refrigerator warranted us to continue to pursue a small centrifugal machine which could be packaged into a U-tube. We finally chose a centrifugal cold compressor manufactured by Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) for the project. We have successfully tested a unit in the Tevatron. It has proven to have very good regulation and turndown characteristics. On many occasions, we hit the unit with two-phase with no adverse effects.

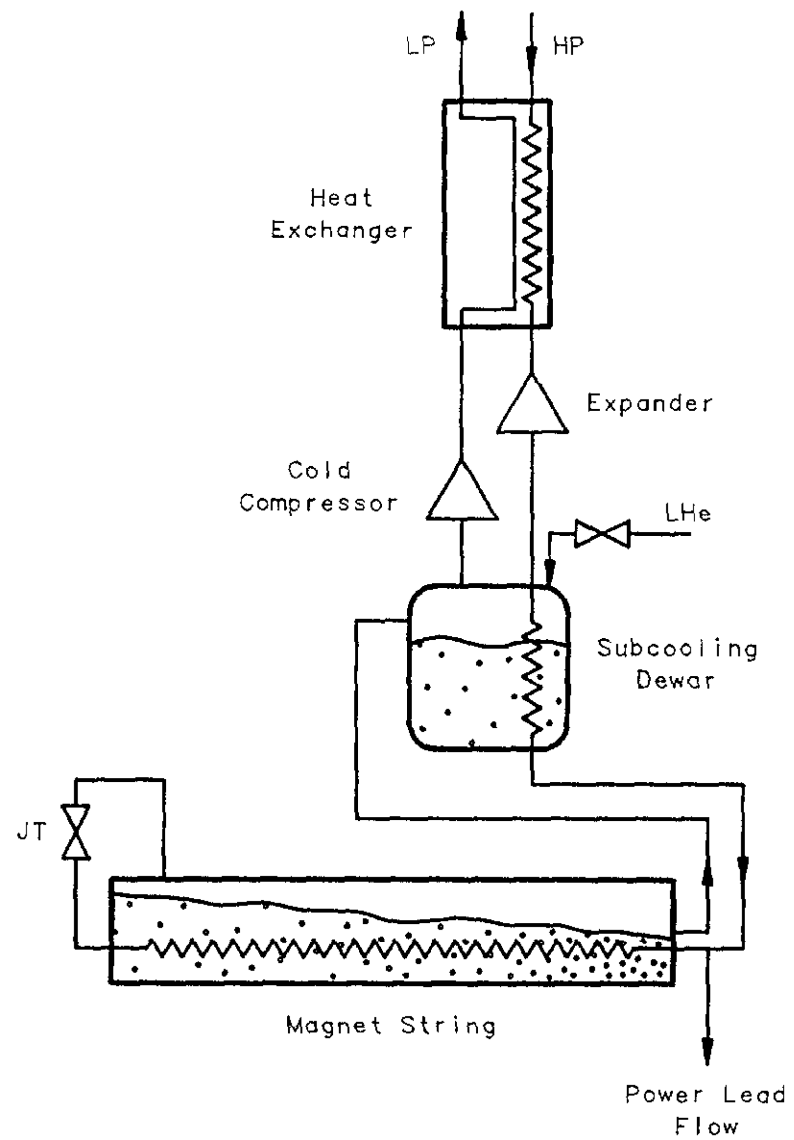

Figure 1. Satellite refrigerator configuration for lower temperature operation.

SATELLITE REFRIGERATOR CONTROLS

Each of the twenty-four satellite refrigerators and eight compressor buildings has its own local microprocessor based controls system. They communicate back through a high speed link to a Main Control room. This allows us to centralize control, alarms, and data logging functions. The added channels of digital and analog information which must be processed for the upgraded satellite refrigerators necessitate a major reworking of the controls.[11] There is no possible expansion of the existing system with which to handle the new information. We are replacing the existing Z80 microprocessor based system residing in Multibus I with a 80386 microprocessor based system in Multibus II.

Since significant technological advances have been made in the microprocessor field since the original refrigerator controls were constructed, it is possible to build a system far more sophisticated than that which has existed to date. With this fact in mind, the upgrade is being proposed in two phases. The first phase adds all the requisite channels on the new platform while retaining the present functionality and means of operation from consoles. The second phase expands upon the existing functionality. Expansion envisioned includes processor to processor communication, a new process control environment, smart alarm system, new control loop structure, and higher level language interface. Processor to processor communication will allow control of refrigerators or compressors based on the status of others. A new process control environment will add a graphical user interface to the existing finite state machine environment, making it easier to generate or debug control code. A hierarchical alarm system is planned to prevent the operator from being swamped with alarms during major events such as a quench, power failure, or operational mode change. Alternatives or additions to the current PID control loop structure will be investigated. The use of artificial intelligence techniques will be considered. A higher level language interface will allow the engineering staff to add on-line engineering calculations in order to incorporate helium properties or to perform on -line efficiency calculations.

For the new system, the calculations and network interfacing take place in the 80386 processor. Each 80386 processor is in turn connected via a local Arcnet link to a temperature monitor chassis and I/O crate. Each temperature monitor chassis and I/O crate is controlled by an 80186 processor and, taken as pairs, are called "secondaries." An important feature of this design is that there is one 80386 per house, so that the existing data structures established for the Z80 system can be maintained. This eliminates a significant amount of programming effort. For Phase II, it is assumed that the compute load for the 80386 processors will rise to require one 80386 per house in any case.

The I/O chassis consists of a number of special purpose modules, primarily constructed in-house, connected by a rudimentary backplane. The software in the controlling 80186 processor will be kept simple by operating it in a data pool mode collecting all possible data at some fixed rate. An additional facility will be the collection of high rate data in a circular buffer mode, to aid in quench studies. A major part of the labor effort will be the cabling associated with this chassis.

Significant software work will be required both for microprocessors and for console applications, in addition to some database additions and modifications. The microprocessor efforts involve generic software (the conditioning of standard products to the refrigerator environment and the creation of the code in the 80186 processor for data acquisition and Arcnet connection); and refrigerator specific code (closed loops, finite state machines, and quench recovery). The application work involves modification of twenty primary and eight secondary application programs.

STATUS AND FUTURE PLANS

We are currently in the middle of a five month shutdown to install the satellite low temperature and controls upgrades. System startup will take place this fall. We will operate the CHL Coldbox II at higher capacity and the satellites will be operating with cold compressors. Power testing will take place to hopefully achieve 1000 GeV operation in the upcoming colliding beam physics run. Considerable time will be required to tune the temperature around the Tevatron at the required level for stable operation of local magnets without wasting refrigeration. This tuning will be important to minimize the burden on CHL, saving operating cost, and wear and tear on the cold compressors. Additional testing and magnet replacements will be necessary to increase the energy further, to the ultimate goal of 1100 GeV.

Future upgrades are planned at CHL to regain full capacity redundancy. Upgrades that are being considered include:

1. Replacement of the turbines in Coldbox I to increase its capacity.
2. The addition of a wet expander in Coldbox I and II to increase capacity and efficiency. Currently a JT valve is used.
3. Upgrade of one of the three original compressors to achieve a 25% increase in capacity as was done in the fourth compressor.

An upgrade in the satellite compressor system is currently under investigation.[12] It involves replacement of the screws and oil used in our Mycom screw compressors. Preliminary results suggest a 13% isothermal efficiency improvement is possible. Payback for such a dramatic improvement would be very short.

ACKNOWLEDGMENTS

The author is grateful to all personnel in the Accelerator Division Cryogenics Department for all the dedication necessary to prepare and commission each of the upgrades. I am also grateful to those in the Accelerator Division Controls Department who have worked on the design and commissioning of the satellite controls system upgrade. The author is also grateful to Jean Poore for the preparation of eight manuscripts in the two weeks preceding the conference.

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