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Supporting the world's highest energy proton/antiproton collider in high energy physics research, the Fermilab Tevatron cryogenic system consists of a hybrid system of a Central Helium Liquefier feeding twenty-four 1 kW satellite refrigerators through a 6.5 km transfer line and supplying the liquid helium for the superconducting magnets of the accelerator and liquid nitrogen for the thermal shielding. Tevatron upgrades have been completed by 1996 and resulted in more than doubling the CHL liquefaction capacity, potential decrease of magnet operating temperatures from 4.9°K to 3.9°K, and proven increase of Tevatron energy from 900 GeV to 990 GeV without losing operational stability.

SYSTEM OVERVIEW

The cryogenic system (see Fig.1) for the Fermilab's superconducting Tevatron accelerator has reached its 13th year of operation. The original design [1] of the Tevatron 6.5 km superconducting ring provided for 777 dipoles, 216 quads, 204 correction elements, and 86 specialty components located in a 2.1 m diameter concrete tunnel buried 6.0 m below ground, distributed refrigeration system located in 24 satellite refrigerator and 6 compressor buildings around the ring above ground, and liquefaction system of the Central Helium Liquefier (CHL) feeding satellite refrigerators through a 6.5 km co-axial transfer line supplying the liquid helium (LHe) for the superconducting magnets of the accelerator and liquid nitrogen (LN_2) for the thermo shielding. The original distributed refrigeration system had a capacity of 23.2 kW at 5°K, plus 1000 liters/hour of LHe to cool the magnet power leads. The original CHL helium liquefaction capacity was 4000 liters/hour. The helium inventory of the cold refrigeration system is 20000 liters, plus additional 10000 liters in the Tevatron transfer line. Losses of the helium inventory are made up via the 60000 liters liquid helium storage at CHL. Gas helium inventory transient control is available via 13 tanks (total volume of 1500 m^3, 1.7 MPa at room temperature). A Nitrogen Reliquefier (NRL), rated at 4680 liters/hour with three stages of compression, Refrigerant 22 precooling, and 151000 liters of liquid nitrogen storage were added to the system in 1985 [2]. NRL provides 80% of the LN_2 consumed for precool during normal 900 GeV operations with the remaining needs supplied from local LN_2 vendors.

Multiple modifications and additions have been made through the years to increase reliability of the cryogenic system, but major upgrades were incporated in 90s to increase the particle energy in the Tevatron accelerator from 900 GeV to 1 TeV [3]. That has been accomplished through a) modification to the satellite refrigeration system to lower the temperature down by 1°K [4]; b) upgrade of the CHL [5]; c) upgrade of the refrigeration control system [6]. By 1995 all listed above upgrades have been completed, the system has been tested, and proven to be reliably functional at 3.93°K, thus providing for an increase of Tevatron energy up to 990 GeV without losing an operational stability [7].

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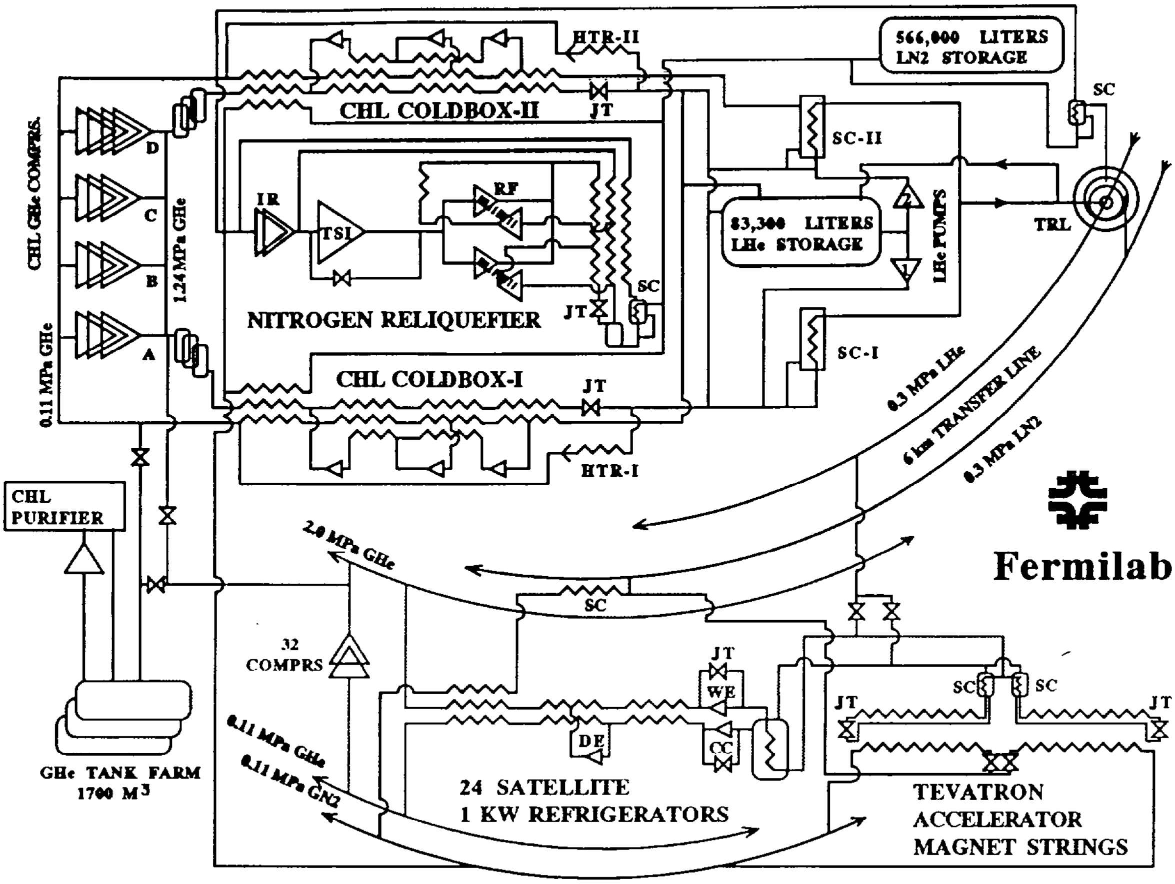

Figure 1 Cryogenic System for the Tevatron

DISTRIBUTED REFRIGERATION SYSTEM

The refrigeration system is divided into six sectors, each consisting of four refrigerators located above ground, ~1 km magnet string in the tunnel, and a compressor building. The system includes eight compressor buildings with total of 32 Mycom 2-stage 300 kW screw compressors which supply high pressure gas helium (2.03 MPa) to the satellite refrigerators coldboxes via a common 75 mm header. The refrigerators use counter flow heat exchangers to cool the high pressure helium flow from room temperature to 5.5°K at the inlet of 5.6 kW "wet" expander. The "wet" expander is controlled with AC variable frequency drive with Mitsubishi regenerative unit. The output of the "wet" expander is routed through a 130 liter subcooling dewar and return flow subcooler to the magnets strings. At the design 4.6°K magnet temperature each refrigerator has a capacity of 625 watts in a standalone mode (using 1.5 kW "dry" expander controlled with a regenerative DC motor/generator) and 966 watts consuming LHe from CHL in satellite mode. The current satellite refrigerator utilizes a new valve box with a 130 liter dewar serving as a phase separator for a "cold" compressor manufactured by Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI). Each "cold" compressor pumps on a dewar to maintain the two-phase pressure as low as 50.7 kPa (0.5 atm) producing 3.56°K helium in the dewar and magnet strings. The "cold" compressor is driven by 1.25 kW induction motor controlled with a Toshiba inverter controller incorporated into IHI control package. All two-phase to atmospheric connections have been "hardened" for reliable subatmospheric operation. The superconducting magnet coils are cooled by subcooled LHe that is continuously counter heat exchanged with two-phase flow. The advantage of a two-phase system is the possibility for uniform temperature over a long distance. There are forty-eight 125 m long magnet strings associated with the Tevatron. Typical temperature for the two-phase is 4.45°K for 900 GeV operations. The superconducting coils operate 10 to 400 mK higher due to heat leak and AC losses.

CENTRAL HELIUM LIQUEFIER

The inceptive design of the Tevatron cryogenic system envisioned redundancy of accelerator operations on either the CHL assisted satellite mode or stand-alone mode with twenty four dry expanders and LN_2 precooling of the satellite system in periods when the CHL was off-line due to failure or trip. However, the refrigeration loads of the accelerator magnet system increased beyond the capacity of the stand-alone mode of the twenty four independent satellite refrigerators, thus making the CHL system vital for normal accelerator operations. The present CHL helium plant consists of: a) four parallel reciprocating compressors (three of 540 g/s, plus one of 750 g/s) rated at 5.1 MW total power; b) hydrocarbon removal system; c) two independent Claude cycle cold boxes rated at 4000 liters/hour and 5400 liters/hour with LN_2 precool; d) helium distribution and storage system; e) helium purification system. Both coldboxes have almost identical design with the plate fin heat exchangers from Altec International Inc., and are tied in parallel to the common compressor suction and discharge headers. Coldbox-I has three oil bearing turbo-expanders (42 kW, 23 kW, 9.5 kW) from Sulzer Brothers Ltd. Coldbox-II has three oil bearing turbo-expanders (58.3 kW, 32.2 kW, 13.2 kW) from Atlas Copco Rotoflow Inc. The equivalent refrigeration capacity can be assessed as 9.6 kW (coldbox-I), plus 12.5 kW (coldbox-II) at 4.6°K. The actual available capacity of the coldbox-I was determined in March 1996 experimentally as 3775 liters/hour (131 g/s) at 1214 g/s inlet flow, and the actual available capacity of the coldbox-II as 5220 liters/hour (181 g/s) at 1500 g/s inlet flow. Two distribution valve boxes and liquid helium pumps are installed in parallel allowing independent operations of either system. The option to operate both systems concurrently exists, thus allowing cool downs and engineering runs with the available compressors. The liquid helium inventory is being increased up to 83300 liters, and gas helium inventory up to 1700 m^3. Also, a reliable supply of liquid nitrogen has proven to be vital for accelerator operation, thus making necessary to increase its total inventory to assure 120 hours of LN_2 backup supply in the event of normal LN_2 production and delivery are interrupted. Therefore the CHL nitrogen inventory is being expanded from 151000 liters to 566000 liters of liquid nitrogen.

NEW CRYOGENIC CONTROL SYSTEM

The Tevatron cryogenic control system is designed to control 24 satellite refrigerators and eight compressor buildings. Data acquisition (~700 data points per refrigerator) is required at the rate of 1 Hz for all data. The new control system is based on a Multibus II platform using Intel 32 bit, 80386 microprocessor. Token ring is used as the link between 6 primary crates (one crate per Tevatron sector) while Arcnet is used as a LAN between the primary crate and individual I/O crates located at each refrigerator or compressor building. New control system features include: processor to processor communications, fast event driven circular buffer, hierarchical alarm system, higher level language support, and more elaborate controlling algorithms with a capability of on-line calculations. Each refrigerator has a cryo thermometry I/O subsystem and cryo device I/O subsystem. Each subsystem I/O uses Intel 16 MHz, 80C186 processor to control all the activity such as settings and readings. Thermometry I/O subsystem provides support for 96 channels of pulsed current, resistance thermometry, and acts as a link to Tevatron quench protection system. The cryo device I/O provides support for transducer input, valve actuator controls, power leads digital controls, vacuum gauge readback, and various motor driven devices, such as expansion engines and compressors. PID loops are easily modified by the operator at a console level. Cooldown of refrigerators and magnets from room temperature, or recovery after a quench are done automatically via specialized finite state machine software.

The CHL control system consists of nine Texas Instrument (now Siemens) PM550 process controllers to implement control, alarm, and interlocks functions for nine major subsystems. The NRL control system is being upgraded to Siemens SIMATIC TI505 process controller and IBM PC-based Wonderware InTouch 5 graphical interface.

HIGH ENERGY TEST

Initial high energy testing took place in December, 1993 and January, 1994. During that time, the Tevatron was uniformly tuned for 75.8 kPa (3.93 K) with cold compressor operation. The ultimate ramp-to-quench energy achieved was 998 GeV. The second major testing sequence took place in July, 1995. Again, the entire Tevatron was tuned for a uniform cold compressor temperature of 3.93 K. An attempt was made to uniformly tune the cold compressor temperatures down to 58.6 kPa (3.69 K) to investigate the increase in quench energy, but the steady state operation were not possible due to capacity limits of CHL coldbox-II. Finally, the recent testing in October, 1995, was to determine the quench energy of the Tevatron while individually tuning the operating temperature of each satellite system until a lower temperature limit was reached in the quench limiting house. A maximum quenching energy of 1010 GeV was achieved. The quenching magnets will need to be replaced in order to proceed to a higher energy, with a goal being 1000 GeV operation for Collider Run-II.

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