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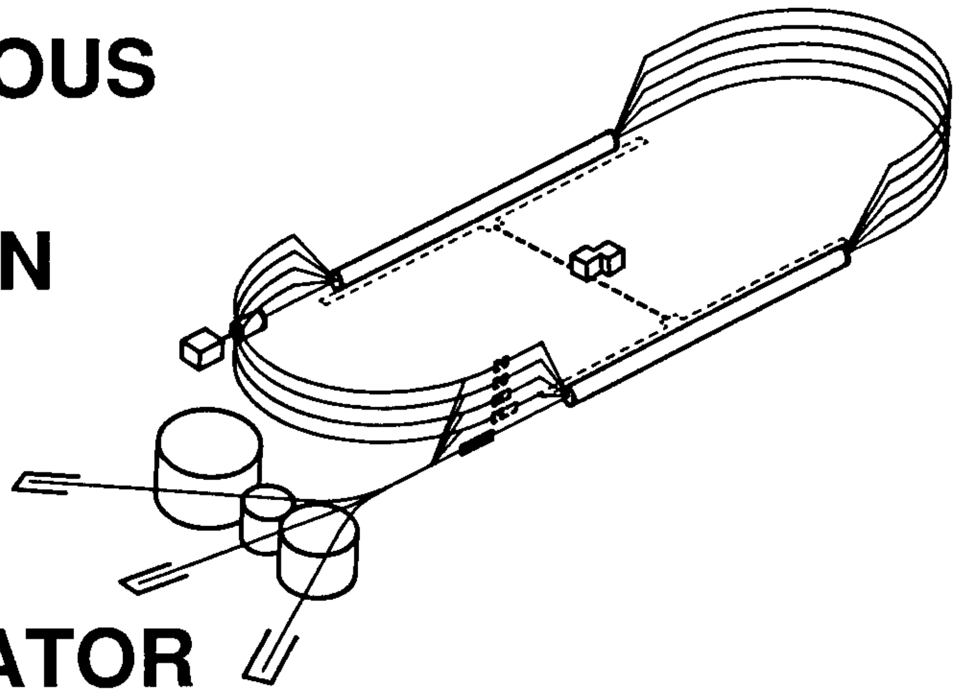

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COMMISSIONING AND OPERATION OF THE CEBAF 2 K REFRIGERATION SYSTEM

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ABSTRACT

The CEBAF Central Helium Liquefier[1] will provide 2 K refrigeration to 338 superconducting niobium accelerating cavities in two 0.4 GeV linacs and one 45 MeV injector. Eight cavities are assembled together to form a single accelerating cryomodule. The 2 K refrigeration system consists of three first stage and three second stage compressors, a 4.5 K cold box, a 2 K cold box, 454,200 L of gaseous helium storage, 113,500 L of liquid helium storage, 75,700 L of nitrogen storage, 10 g/s helium purifiers, gas recovery compressors, and 2.0 km of cryogenic transfer lines. At full capacity, the Central Helium Liquefier will provide 4.8 KW of primary refrigeration at 2.0 K and 12 KW of shield refrigeration at 45 K.

INTRODUCTION

Commissioning of the Central Helium Liquefier was divided into subsystems to co-ordinate, analyze, and evaluate the performance of each subsystem and its associated controls. The major subsystems were main helium compression, gas management and storage, helium purification, 4.5 K cold box, liquid nitrogen storage, and a helium supply transfer line. A temporary 0.031 bar vacuum system was commissioned to support a low flow (15 g/s) 45 MeV injector test.

The cycle design for the CEBAF refrigeration system is shown in T-S diagram form in Figure 1.[2] Two stages of oil injected helium screw compressors provides 1578 g/s of flow at 20.1 bar and 305 K to the 4.5 K cold box. The flow is cooled to 80 K by liquid nitrogen precooling and heat exchanging cold gas returning to the compressors. Turbines D1, D2, and D3 provide 31, 23 and 14 KW of refrigeration respectively. The D1 turbine discharge flow will be used to provide 12 KW of refrigeration for transfer lines and cryomodule shields.

Turbine D4 will provide 448 g/s of refrigeration from 8.2 K and 20.1 bar to 4.5 K and 2.8 bar. A design provision is made to supply 10 g/s of the D4 discharge flow to CEBAF End Stations which are now under construction. Flow from the End Stations will be returned to the interstage of the main helium compressors. The D4 turbine discharge flow will also be used to liquefy approximately 4,000 L/HR into a 113,500 L helium dewar at 4.42 K. The liquid storage will be used to supply the cryomodules with cryogens in the event the CHL becomes inoperative or if its refrigeration capacity has diminished.

Normally, the D4 discharge flow is subcooled by heat exchanging with 2.0 K load return flow to the suction of the cold compressors (CC1-CC4) in the 2 K cold box. After subcooling, separate 2.8 bar supply transfer lines[3] will supply and distribute the 2.2 K helium to the CEBAF North and South Linac. The supply transfer line for the North Linac is operational at the present time and is providing cryogens to cryomodules in the 45 MeV Injector.

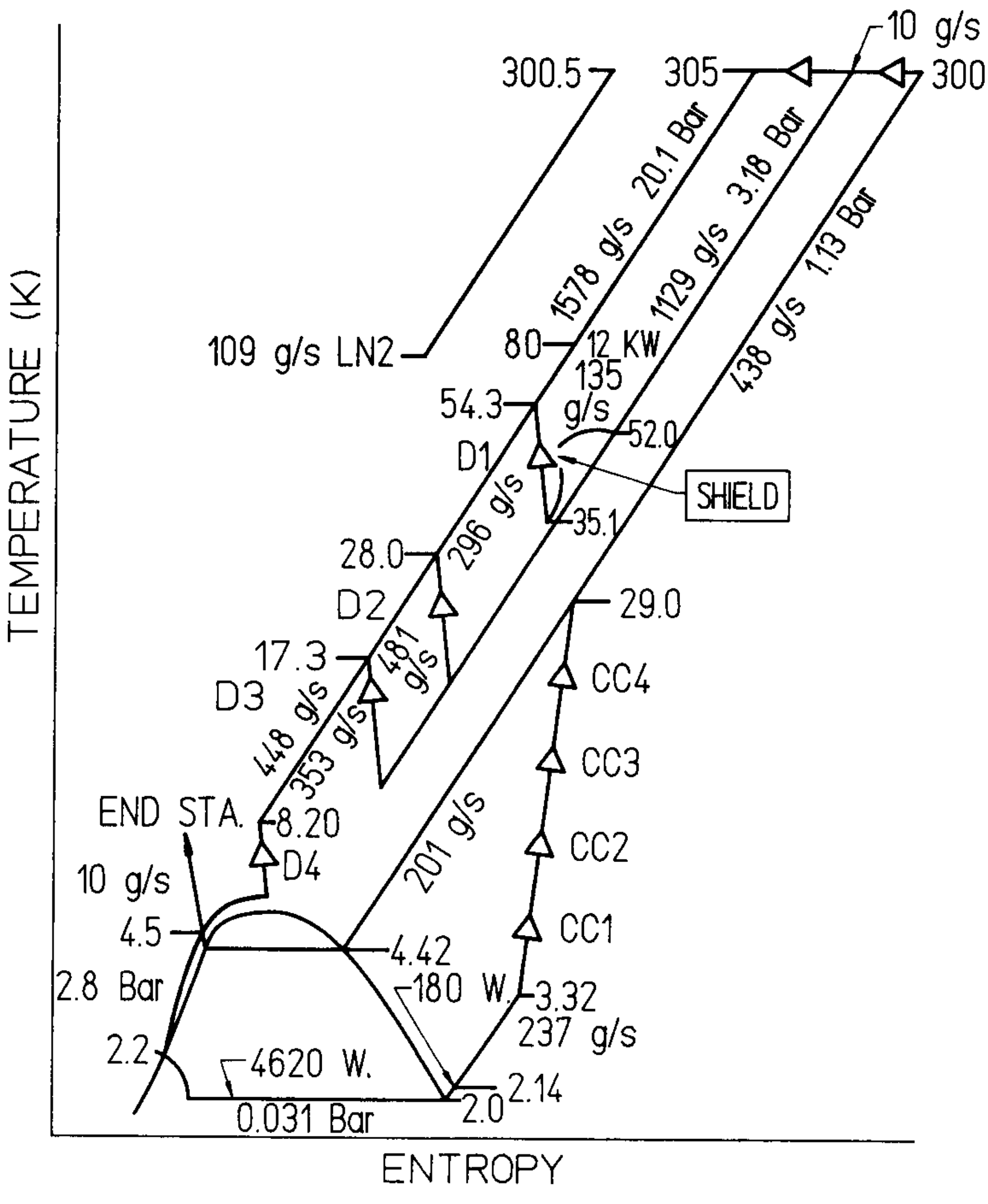

Figure 1. CHL TS diagram

Flow from the supply transfer line is expanded through a J-T valve to 2.0 K and 0.031 bar at each cryomodule location in the linacs and injector. At a maximum load of 4.8 KW, 237 g/s of return flow would return through a 0.031 bar return transfer line to the 2 K cold box. Four stages of cold compressors in the 2 K cold box will compress the cryomodule return flow from 0.031 bar to 1.18 bar and inject the flow into the 4.5 K cold box return line at 29 K. The low pressure return flow then is used to heat exchange with 4.5 K cold box supply flow and is returned to the first stage compressor suction.

The main helium compressors, 4.5 K cold box, 2.8 K supply transfer line, gaseous helium storage, liquid nitrogen storage and their respective controls have been commissioned. Presently, they provide reduced 2 K refrigeration to two and one quarter cryomodules for a 45 MeV injector beam test. Because the beam test 2.0 K flow requirement is low, a 15 g/s liquid ring pump and blower is used to provide an 0.031 bar operating pressure for the cryomodules. Computer control programming is now underway in preparation of commissioning the 2.0 K cold box. Performance testing of the 4.5 K cold box will be completed with the commissioning and performance testing of the 2.0 K cold box and cold compressors.

HELIUM COMPRESSOR SYSTEM

The compressor system is shown in block diagram form in Figure 2. The system consists of 8,000 liquid L equivalent of 16 bar gaseous helium storage and gas management controls. The system consists of two stages of Howden 321 mm oil injected screw compressors with three compressors in each stage. The rotor length to diameter ratio for the first and second stage is 1.65 and 1.3, respectively. The first stage compressors provide an operating compression ratio of 2.95 with a 1.13 bar suction pressure. The second stage compressors provide a nominal compression ratio of 6.3 with a 3.2 bar suction pressure. Two first stage compressors and three second stage compressors are required to achieve the CHL T-S flow diagram requirements.

Gas management controls include gas make-up into the discharge of the first stage from gas storage to maintain second stage discharge pressure at 20.1 bar. A secondary gas make-up into the suction of the first stage is also available. The first and second stage suction pressures are maintained by a discharge to suction by-pass valve which senses suction pressure of each stage. Typical control setpoints for these valves are 1.13 and 3.18 bar. A mass-out control valve allows compressor discharge flow to return to gas storage whenever the discharge pressure exceeds 20.3 bar.

Compressor slide valves were operated to computer controlled fixed positions during the full compressor load evaluation. The by-pass valving proved to be very responsive to pressure fluctuations and control of the compressor suction and inter-stage pressures.

Because of compressor slide valve control non-linearity, slide valves will be used to maintain coarse minimal compressor bypass valve control to conserve electrical power. Compressor nominal power requirements were 0.40 and 1.2 MW for each fully loaded first stage and second stage, respectively. Compressor bypass valves were sized for full compressor flow capacity. The compressor system can be fully isolated from the 4.5 K cold box while maintaining full design flow. Pitot tubes provide flow measurement to and from each compressor stage.

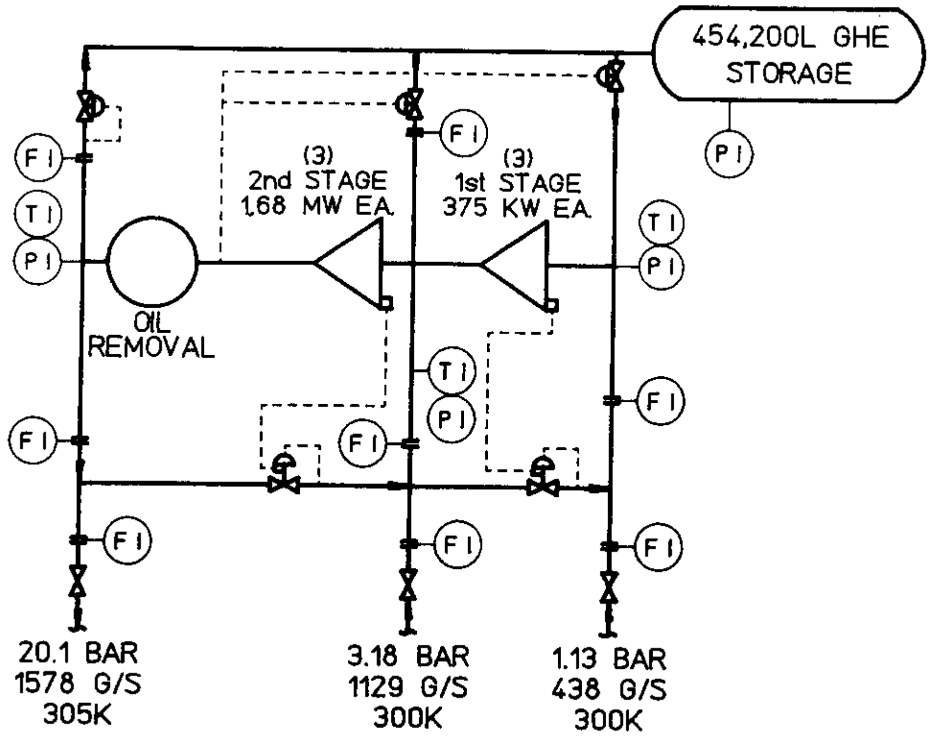

Figure 2. CHL compressor system

Flows are pressure and temperature compensated by the computer control system to provide mass flow measurements in grams per second. Flow measurements have accurate turndowns ratios of 3 to 1. Flow mass balance during compressor testing was typically within 3 percent. An indicated discharge flow rate of 1590 grams/sec was achieved by the compression system at the process design conditions with three fully loaded second stage compressors and two first stage compressors running.

Cooling water requirements for each compressor is a minimum of 732 L per minute for the first stage and 2000 L per minute for the second stage with a allowable temperature rise of 11 °C (20 °F). Each compressor is equipped with a bulk oil separator and double tube sheets, U-tube design aftercooler and oil cooler. Three stages of oil coalescers and an oil vapor charcoal adsorber are provided at the second stage discharge. All electrical safety interlocks for the compressors are "hard wired" to local compressor control panels. A control switch for each compressor transfers control to the CEBAF computer control system.

The compressors were first commissioned in October of 1990. Two first stage and two second stage compressors have operating almost continuously since February of 1991 with 2000 hours of operation each. At the present time, these compressors are used to support the CEBAF 45 MeV Injector Test. The compressor configuration for this mode of operation is shown in Figure 3 for unloaded injector cryomodules.

Two 375 KW (500 HP) first stage compressors are partially loaded to 80% of slide valve position for a combined 0.58 MW of electrical power consumption and 247 g/s flow rate. The suction and discharge pressures of the first stage compressors are controlled at 1.13 and 3.18 bar, respectively. Approximately 10 g/s of make-up flow is continuously injected into the interstage to maintain constant liquid levels within the cryomodules. The interstage return flow from the 4.5 K cold box provides an additional 510 g/s of flow to the suction of the second stage. Two 1.68 MW (2250 HP) second stage compressors are fully loaded to provide 767 g/s at 20.1 bar to the 4.5 K cold box. The second stage compressors have a combined 2.4 MW electrical power consumption. A modest amount of bypass flow around each compressor is maintained to control pressures.

4.5 K COLD BOX

Performance testing of the 4.5 K cold box is scheduled to be completed with the commissioning of the 2 K cold box and cold compressors. Each of the four turbines were started and operated to check mechanical integrity. It was during these tests that the cold turbine, D4, thrust bearings failed twice. The use of turbines D1 and D4 would have provided better efficiency for the 45 MeV test permitting operation with only one first and one second stage compressor. CEBAF is presently using turbines D1 and D3 for reduced refrigeration. The present operation of the 4.5 K cold box is depicted in Figure 3.

The 767 g/s of compressor discharge flow is precooled to 80 K by the 4.5 K cold box return flow and liquid nitrogen. The indicated liquid nitrogen usage of 5 L/M is a combined nitrogen use for the cryogenic purifiers and the 4.5 K cold box precooling. Flow enters turbine D1 at approximately 49 K. The D1 turbine discharge pressure is regulated by a back pressure control valve to maintain 3.45 bar. A 38 K shield flow of 5 g/s is diverted from the discharge of D1 for shield cooling of the injector cryomodules. Two of the five grams per second is bypassed at the ends of the shield transfer line to maintain shield transfer line temperatures. The installation of the return transfer line to the 4.5 K cold box has not been completed. As a result, the shield return is warmed to 300 K by 16 KW of electric heat and returned to the first stage compressor suction. The heater does have a benefit, however, of adding a heat load onto the large helium refrigeration system for this mode of operation.

Flow enters the D3 turbine inlet at approximately 17 K. The combined 510 g/s flow of the D1 and D3 turbine exhaust returns through interstage passages of the 4.5 K cold box heat exchangers and enters the compressor interstage.

The 20.1 bar gas which does not enter the inlet of turbine D3 is throttled through a valve (V130) which has been locked to a fixed open valve position. The pressure down stream of V130 is regulated at 2.8 bar by a J-T valve (V122) which bypasses 240 g/s directly into the 1.13 bar heat exchanger pass of the 4.5 K cold box. Control valve V116 regulates the inlet temperature of the D3 turbine at 17 K. If the inlet temperature to D3 decreases below 17 K, the V116 valve opens further to bypass more return 1.13 bar flow around the low pressure heat exchanger return passes of the 4.5 K cold box. The bypass flow is diverted into the 80 K heat exchanger injection point. If the inlet temperature to D3 increases the diverter valve, V116, closes forcing more flow through the return of the 4.5 K cold box heat exchangers.

The balance of the flow (12 g/s) upstream of the J-T valve V122 is diverted through the supply transfer line to the North Linac Tunnel. In the tunnel the transfer line joins into a supply transfer line header which runs east and west for approximately 300 meters.

At the east and west ends of the supply transfer line header, valves bypass 1 g/s each (2 g/s total flow) to maintain a minimal cooling flow within the transfer line. This bypass flow is presently heated to 300 K by electric heaters and returned to the suction of the 1st stage compressor using ambient temperature piping. When the return transfer lines are completed, these bypasses will be returned to the 4.5 K cold box to recover refrigeration. The remaining 10 g/s flow of transfer line flow is currently being used to supply the 45 MeV injector test cryomodules at the west end of the North Linac.

At the test cryomodule locations, temporary J-T valves and 26 L phase separators are provided for each cryomodule. The J-T valves flash the subcooled transfer line vapor into the separators to maintain a 50 percent liquid level in the separators. The pressure is maintained at approximately 1.1 bar by the suction pressure controls of two helium recovery compressors. The vapor return from the phase separators is heated to 300 K with a 8 KW electric heater and is returned to the suction of the recovery compressors.

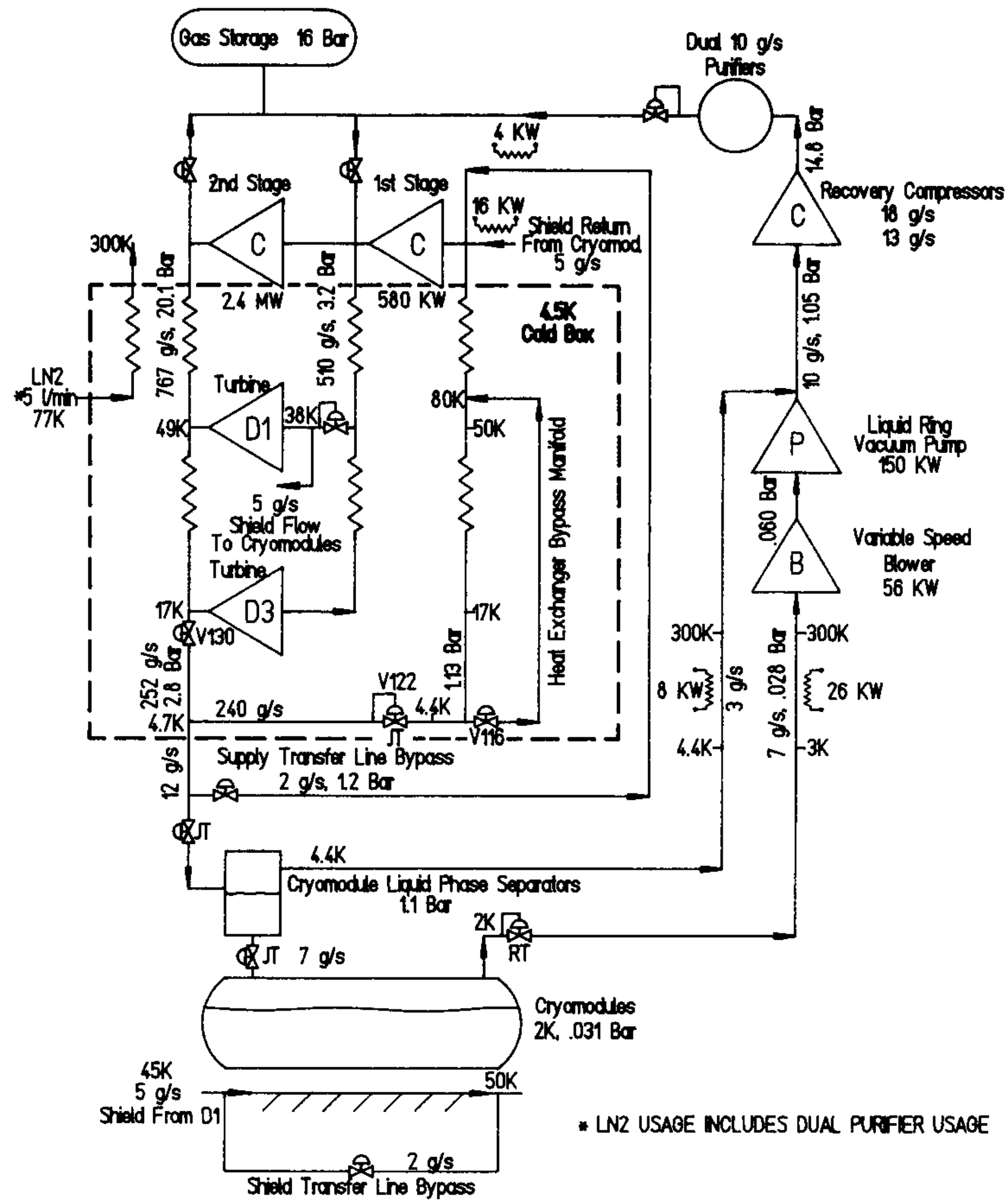

Figure 3. No load cryomodule 2 K operation

The liquid of the phase separator flashes through the J-T valve of each cryomodule to maintain a 90 percent cryomodule liquid level at 0.031 bar and 2 K. The cryomodule pressures are maintained by a 150 KW (200 HP) liquid ring vacuum pump, a 56 KW (75 HP) variable speed blower, and a back pressure control valve on each of the cryomodules. Typical pressure regulation is $\pm 1 \times 10^{-4}$ bar.

The return flow from the cryomodules is heated to 300 K by 26 KW of electric heat. The discharge of the vacuum pumps is controlled at 1.05 bar by the bypass pressure controls of two helium gas recovery compressors. One or both of the compressors may be used depending on the amount of return flow rate. The helium gas is compressed to 14.8 bar and purified before being returned to the helium gas storage. Typical contamination levels returning from the cryomodules has been less than 1 PPMv of water and nitrogen.

CONTROL SYSTEM

The CEBAF 2 K refrigeration system has been designed for unattended operation. Each subsystem is equipped with local safety interlocks which are independent of the CEBAF computer system. Local controls are provided for operation of individual compressors, turbines, and other rotating equipment which are necessary for maintenance, testing, etc. Controls which are necessary to the regulation of performance or process conditions of the system are interfaced to the UNIX based CEBAF computer control system via CAMAC I/O interface racks. The system runs on the HP 300 and 800 series computers. CEBAF utilizes a software system known as Thaumaturgic Automated Control Logic (TACL) which was developed to operate large scale particle accelerator facilities. TACL is programmed in C language. TACL provides a graphic, menu display screen generator system. This has allowed many of the control display screens used for the refrigeration system to be developed by CEBAF summer students.

CONCLUSIONS

CEBAF has commissioned the 2 K refrigeration system for operation in a turndown refrigeration mode. This mode of operation supports CEBAF 45 MeV injector testing. The helium compression system has been tested under the process conditions of the design T-S diagram. A complete refrigeration test of the combined compressor, 4.5 cold box, and the 2 K cold box performance will be performed in the near future. Operational experience has been gained for the helium compressors and the 4.5 K cold box.

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