2.0 K CEBAF CRYOGENICS

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INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) is a standing wave superconducting linear accelerator with a maximum energy of 4 GeV and 200 μA beam current. Three hundred and thirty-eight superconducting niobium accelerating cavities are arranged in two 0.4 GeV linacs with magnetic recirculating arcs at each end. The beam may pass through the linacs up to five times; there is one recirculating arc for each energy (see Figure 1). The beam is then transported to the three experimental halls (end stations).[1]

CEBAF's refrigeration is provided by three semi-independent cryogenic systems; they serve the Test Lab, linacs, and end stations respectively. The site plan, Figure 2, shows the three systems. The Cryogenic Test Facility (CTF) is currently operational. The Central Helium Liquefier (CHL), as well as its building, are nearing completion with installation scheduled to start in early fall. The End Station Refrigerator (ESR) is scheduled for FY91.

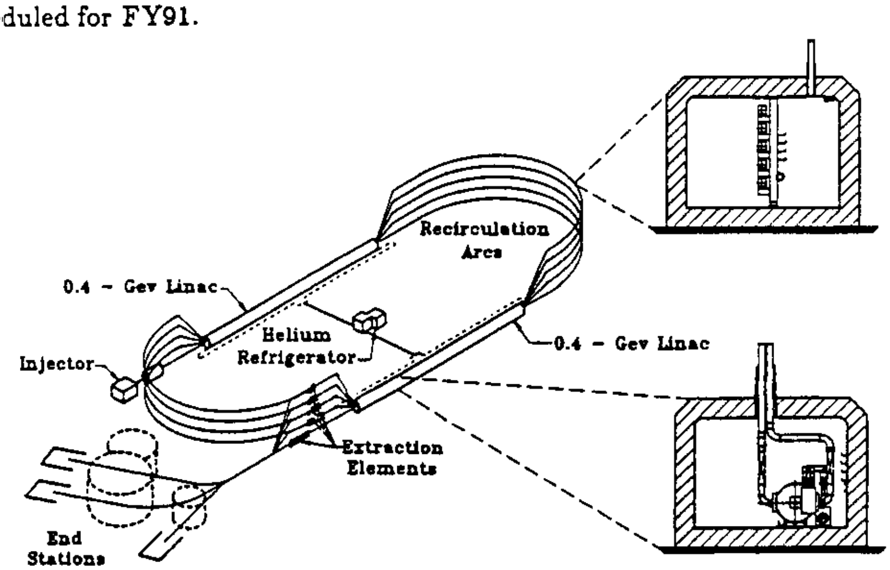

Figure 1: Accelerator Layout

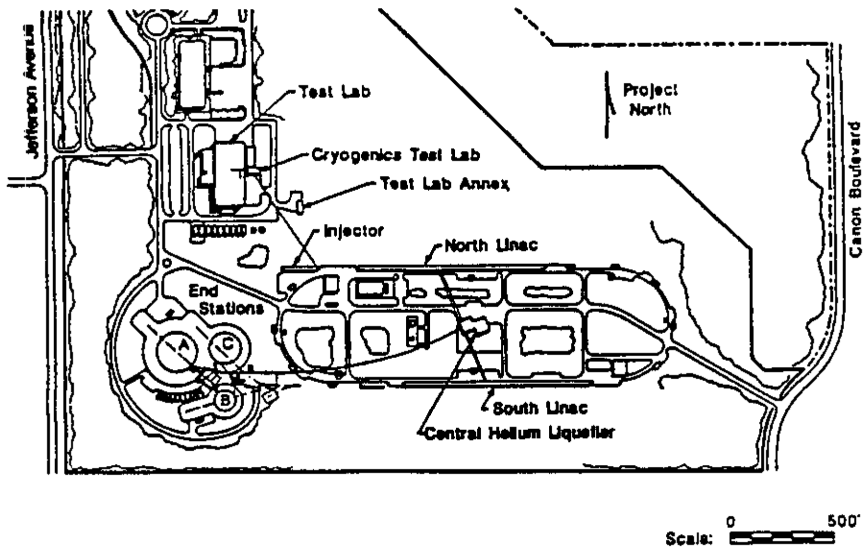

Figure 2: CEBAF Site Plan

The capacities of the three refrigeration systems are given in Table 1. The CHL consists of three first stage and three second stage compressors, the main cold box (which produces 45 K and 4.5 K refrigeration), the subatmospheric cold box (which lowers the temperature from 4.5 to 2.0 K), 110,000 L of liquid helium storage, and 75,000 L of liquid nitrogen storage. A pair of transfer lines provides two parallel cooling loops to each cryomodule. The line sizes vary from 17 to 41 cm in diameter, with a total length of 1400 m.

The ESR is the LBL "ESCAR" refrigerator consisting of a single pair of compressors and a single cold box. Each of the three halls has its own independent transfer line with a nitrogen shield supply and a 4.5 K refrigeration loop.

Table 1
Refrigeration Capacities

	He Temp. (K)	Capacity (W)	Pressure (atm)	Flow (g/sec)
CHL				
Linac shields	35–52	12,000	4.0	136
Linac cavities	2.0	4800	0.031	240
Liquefaction	4.5	288 l/hr	2.8	10
ESR				
Magnet shields	85	LN_2	3.0	NA
Magnet	4.5	675	2.8	45
Magnet power leads	4.5	216 l/hr	2.8	7.5
CTF				
CB#1 – Shield	40–60	800	3.0	16
CB#2 – Refrigeration	4.4	700	2.8	40
CB#3 – Liquefaction	4.6	58 l/hr	1.4	2
CB#4 – Refrigeration	2.0	150	.031	10

The CTF consists of three compound screw compressors in parallel, four medium-sized cold boxes, and a 10 g/sec vacuum pumping system. The choice of four cold boxes was driven by availability of equipment, as well as the need for a very flexible system to service many independent users. It should be noted that cold box 4 is a satellite refrigerator and uses 2 g/sec of 3 K gas from cold boxes 2 and 3.

TEMPERATURE SELECTION

Cryogenics is required for both the 338 superconducting rf cavities and the end stations, but not for the nine 180° arcs. The arcs are conventional because the highest-energy one is only 0.5 T—well below the economical minimum for a cryogenic bend.

Superconducting cavities require a cryogenic system to cool them from ambient temperature to the operating temperature. This operating temperature must be below the superconducting transition point for niobium, 9.2 K. To maintain the temperature, a balance is required between the total heat load of the cryomodules and the capacity of the cryogenic system to remove the generated heat. Additional capacity is required for reliability as well as cooldown.

There are two types of resistive losses in a superconducting rf cavity: residual resistance and BCS resistance (Bardeen, Cooper, and Schrieffer). The residual resistance is caused by localized resistive areas where defects, impurities, or surface dirt disturb the superconductive properties. The BCS resistance increases with increasing frequency and decreases as the operating temperature decreases. Other sources of 2 K heat load include static heat leak, conduction of heat dissipated in the input waveguide, and absorption of higher-order-mode power generated by the beam currents.

The choice of operating temperature affects the BCS component of the cavity Q and thereby the rf heat load, as well as the refrigeration capital and operating costs. The BCS losses vary with the cavity Q, approximately doubling every 0.2 K. Figure 3 presents the total heat load as a function of temperature. The refrigeration costs vary inversely with the temperature; in addition, capital costs increase with the 0.7 power of heat load, while operating costs increase to the 0.85 power. The net effect is shown in Figure 4.[2]

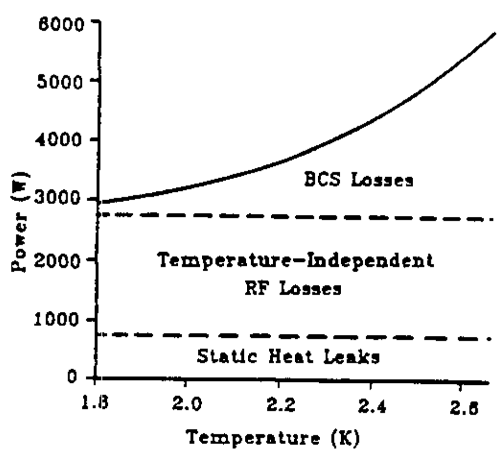

Figure 3: Total Heat Load as a Function of Temperature

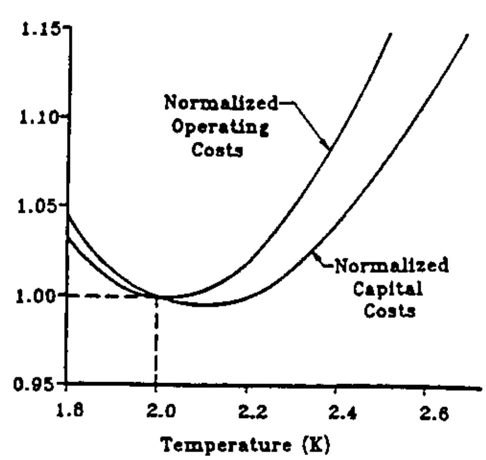

Figure 4: Normalized Costs

We have chosen 2.0 K as the operating temperature. The BCS losses, while an exponential function of temperature, are still a small fraction of the total heat load at 2.0 K. Figure 4 shows that the refrigeration capital cost is flat to 0.5% between 2.0 and 2.2 K. Below 2.0 K not only is it not cost-effective, but it also becomes technically difficult due to the very low vapor pressures (less than 0.031 atm). Above 2.5 K (0.1 atm) we could delete one stage of vacuum pumping, but the BCS losses are so large that it would not be economical.

This leaves us with an operating range of 2.0 to 2.5 K. Since possible future higher cavity gradients will tend to shift the optimum toward lower temperatures, 2.0 K will permit future beam energy increases.

The end station refrigerator (ESR) cools many large superconducting magnets for spectrometers. Magnets gain much less for a lower operating temperature; the conductor improves by only 33% as one lowers the temperature from 4.4 to 2.0 K. We therefore have chosen a coil bath temperature of 4.5 K, which corresponds to a refrigeration return operating pressure of 1.2 atm and a temperature of 4.424 K.

CENTRAL HELIUM LIQUEFIER

The CEBAF refrigeration system is shown in block diagram form in Figure 5 and in T-S form in Figure 6. The primary systems are the screw compressor system, a standard cold box, the 4.4 K dewar system, the distribution system, and the cold compressor system.

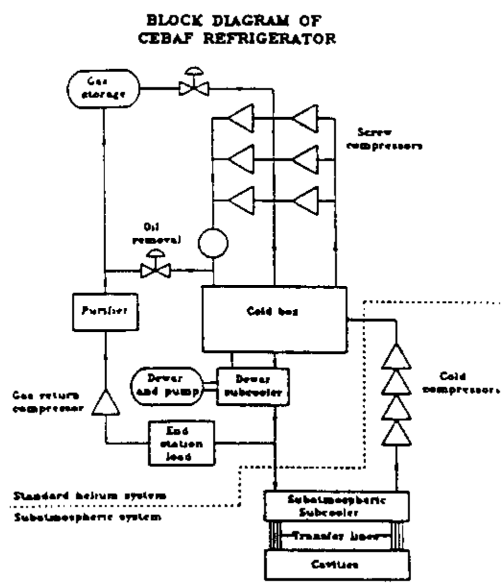

Figure 5: CHL Block Diagram

We have chosen this configuration because it almost completely decouples the standard refrigerator from the subatmospheric system. This decoupling of the cycles has several advantages. From a commissioning standpoint it breaks the cryogenics into a standard off-the-shelf refrigerator and a "high tech" subatmospheric module, which in turn also simplifies the operation and controls. The requirement for double seals with a guard vacuum to eliminate air leakage therefore applies only to the subatmospheric module.

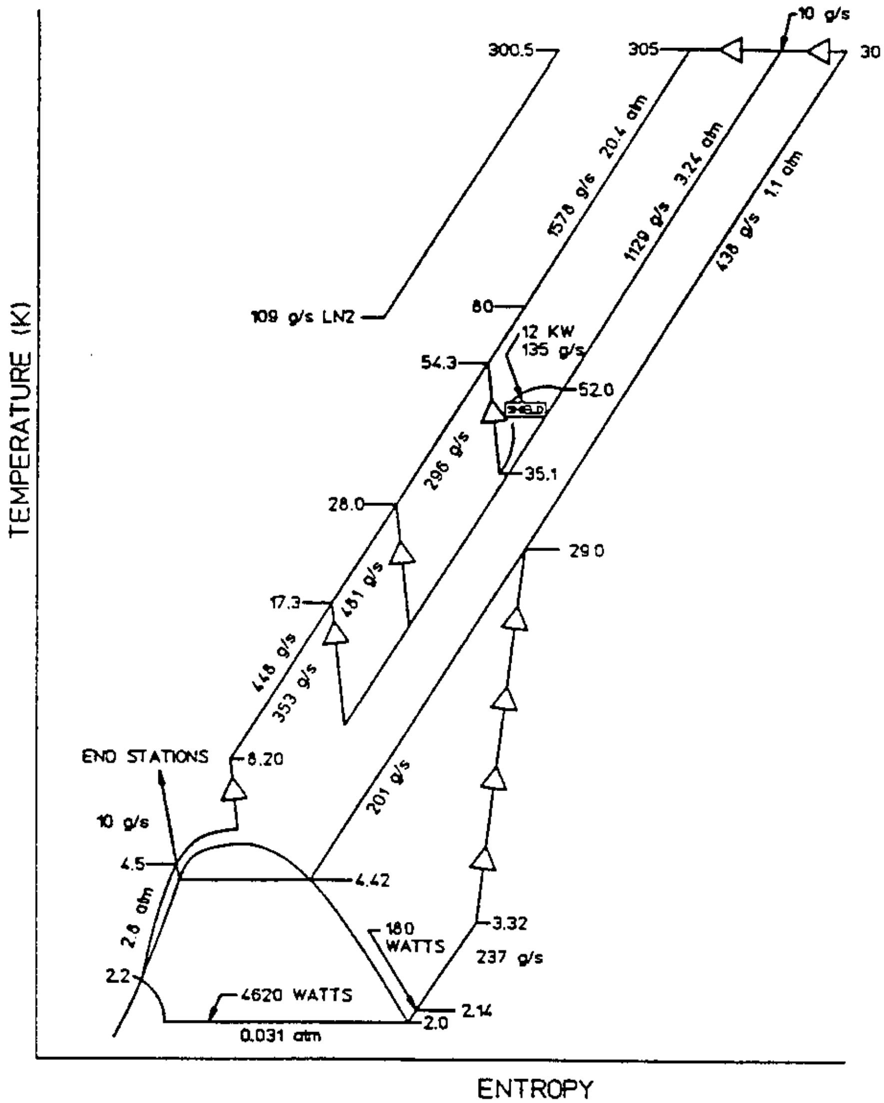

Figure 6: CHL TS Diagram

The cycle can be broken into three parts. Above 30 K we have a standard refrigerator with only a small amount of liquefaction for the end stations. We have two stages of oil injected screw compressors which supply 20 atm helium to the cold box. Helium is cooled to 80 K by heat exchanging the returning helium gas, with a few percent passing through an independent nitrogen precooler. This exchanger is separate to prevent the nitrogen from freezing and cracking the exchanger. The D1 turbine supplies 31 kW of refrigeration to provide for shield cooling and the losses between 80 and 30 K.

Between 30 K and 5 K the cycle is designed as one would find in a pure liquefier, since both the linac and end station return flows bypass this part of the cycle. Due to this imbalance flow, the D2 and D3 turbines must provide 23 and 14 kW of refrigeration respectively. This is understandable when one realizes that the cold compressor adds 28 kW of heat to the cycle.

Below 5 K in steady state the cycle is designed as a pure refrigerator. During the cavity fill cycle, while we are transferring liquid from the 4.5 K dewar to the 2.0 K cryomodule (cavity cryostat), we are operating as a 2.0 K liquefier. This in turn means that there is a severe flow imbalance in the subatmospheric subcooler. An alternate mode is to first fill the 2.0 K cryomodule with 4.5 K liquid and then refrigerate to 2.0 K. The implication of this is that the cold compressor must be able to operate steady-state at a continuum of elevated pressures. The consequences of this on the overall cycle and hardware were analyzed by the refrigerator manufacturer. We have chosen the latter mode since the cold compressors approach their limits of operation at the nominal compression ratio and an elevated inlet temperature of 4.5 K. This, and turn-down capability, are the two primary off-design modes.

Some additional features worth noting are that the refrigerator may operate as a conventional 1.2-atmosphere, 4.4 K helium refrigerator by simply turning off and bypassing the cold compressors. The refrigerator may operate at reduced capacity if any of the expanders are off for repair, or it can operate at close to full capacity for up to three days by consuming liquid.

HARDWARE

The central helium liquefier consists of a large section that is a commercial helium refrigerator and a subatmospheric system to lower the temperature to 2.0 K as presented in Figure 7. The separation of the refrigerator into two sections will insure that if future modifications to the 2.0 K cycle are required, they will not affect the majority of the equipment.

The central helium liquefier will include the following main components: compressors, heat exchangers arranged in a vacuum vessel called a cold box, expanders, cold compressors, and a control computer.

The compressors will be two stages of oil-flooded screw machines which have become the standard for large helium refrigerators and which are extremely reliable. The first stage uses two units operating at 98% of full load and a standby spare. The second stage uses three units operating at 78% of full load; with one off, the interstage pressure increases to 3.9 atmospheres, and one can continue to operate at about 88% capacity.

Figure 8 shows the main cold box, tee-shaped, with the heat exchangers in the vertical cylinder. The horizontal cylinder contains the valves and four turbines. The turbines will have pressurized gas-bearings. They have enjoyed an excellent record of reliability, and large units have efficiencies in the range of 70–80%. The CEBAF refrigerator will use three turbines in parallel, operating between 20 atmospheres and 3 atmospheres to optimize the overall cycle efficiency. The fourth turbine in the main refrigeration flow provides an additional 5 kW of refrigeration over the performance of a Joule-Thompson (J-T) valve in this location. The turbine will be supercritical to prevent transfer line two-phase flow instabilities.[3]

The warmest expander, D_1, will have redundant independent inlet filters. The independent inlet filters are required to trap low-level contaminants such as water and dust. The remaining three turbines do not have redundant filters, but all four are installed in a configuration permitting the replacement of the wheel or cleaning of the filter while the refrigerator is operating. During repair, the system can be kept at full capacity by consuming liquid from the storage dewar and converting it into refrigeration.

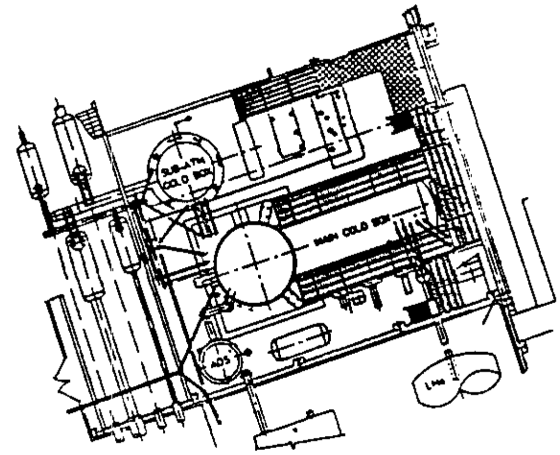

Figure 7: CHL Cold Box Plan View

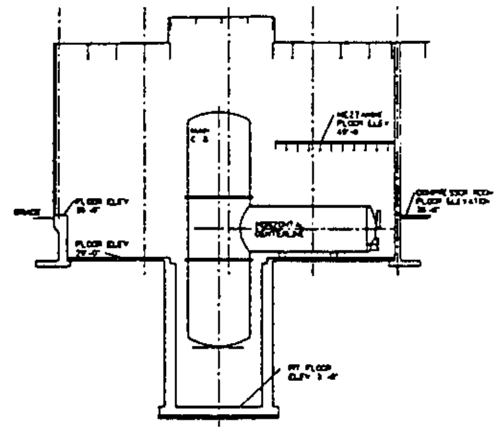

Figure 8: CHL Cold Box Elevation

The subatmospheric subcooler must be large enough to handle the low pressure helium (0.031 atmosphere) returning from the linac cryomodules, but due to the low temperatures it is relatively small. The design of CEBAF's refrigerator is based upon the use of four cold compression stages from 0.031 atmosphere to 1.2 atmospheres. This design avoids the difficult and expensive problem of extremely low pressure heat exchangers which would become huge due to the low pressure drop requirement.

The cold compressors are at the forefront of helium refrigeration technology. The requirements of high throughput and exceptional reliability demand the use of centrifugal compressors. These machines are now in use as a result of extensive development by L'Air Liquide. These essential components provide the low-temperature compression to maintain both the operating conditions (0.031 atmosphere, 2.0 K) in the cryomodules and the positive pressure in ambient suction piping and compressors (1.05 atmosphere).

The main heat exchanger piping will provide gas return locations from the cold compressor discharge at about 300, 56, 38, 26, 18 and 6 K. This will permit cooldown as well as off-nominal design operation.

The control system is an in-house design and is described in Reference 4.

CRYOGENIC TEST FACILITY

This facility provides 4.5 to 2.0 K refrigeration and liquefaction to multiple users. These include production testing of cavities, cryomodules, and end station magnets, as well as injector R&D and advanced accelerator cavity R&D. Figure 9 shows the Test Lab layout, including the CTF refrigeration building located behind the Test Lab shielding wall next to the electronics building. Two penetrations through this wall are used for cryogenics: 1) a six-foot-square tunnel, and 2) a cable duct under the wall. The tunnel contains the cryomodule/vertical dewar transfer line, 32 cm vacuum header, and cable runs. The cable duct contains the CTF end station/injector transfer line.

The refrigeration system consists of three 58 g/sec screw compressors, four cold-boxes, and a helium vacuum pumping system.

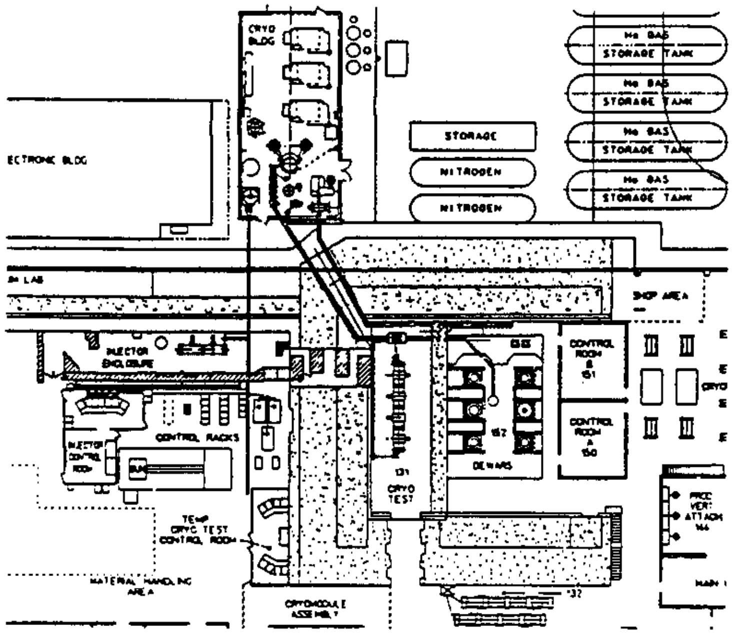

Figure 9: Cryogenic Test Facility

The system is designed to deal with many simultaneous users; it provides four groups of bayonet connections. These are:

A. Cryomodules
B. Injector cryounit
C. Vertical dewars
D. End station magnets

The CTF Load is an order magnitude smaller than the CHL and is more varied. This has made it impossible to use the cold compressor technology here. We are using an oil injected, variable-speed roots blower backed by a liquid ring pump.

The cryomodule and the vertical dewars are cooled to 2.0 K from ~ 3.0 K or 4.5 K liquid by vacuum pumping with the warm vacuum pump, nominally 10.0 g/sec at 2.0 K or 2.0 g/sec at 1.6 K. The injector cryounit is cooled to ~ 2.0 K by flashing 4.5 K liquid. The end station magnets are cooled by a 4.5 K refrigeration loop.

The end station magnets require slow cooldown with controlled temperature differentials to limit stresses. We plan to use the same technique planned in the final end stations. CTF will supply liquid to a mobile exchanger which provides the cooldown refrigeration.

TRANSFER LINE

The economies of scale and cold compressor technology have forced CEBAF to use centralized refrigeration. We therefore have 1400 m of transfer lines varying from 11.4 cm to 40.6 cm diameter. These lines are based on the Fermi Lab Tevatron Transfer Line Design.[5] Module lengths are 24.4 m above ground and 19.2 m in the tunnel.

Figure 10 shows the pair of "H"-shaped linac transfer lines which provide the 2 K and 45 K refrigeration loops for the cavities; Figure 11 shows the flow schematic. The bayonet is provided for quick replacement of cryomodules. We transport 2.2 K (2.8 ATM) supercritical helium to the cryomodules where we J-T to 0.031 ATM, producing 85% superfluid into the 60-cm-diameter cavity cryostats. The boil off gas is returned to the cold compressor by way of 15.3 and 21.4 cm ID transfer lines.

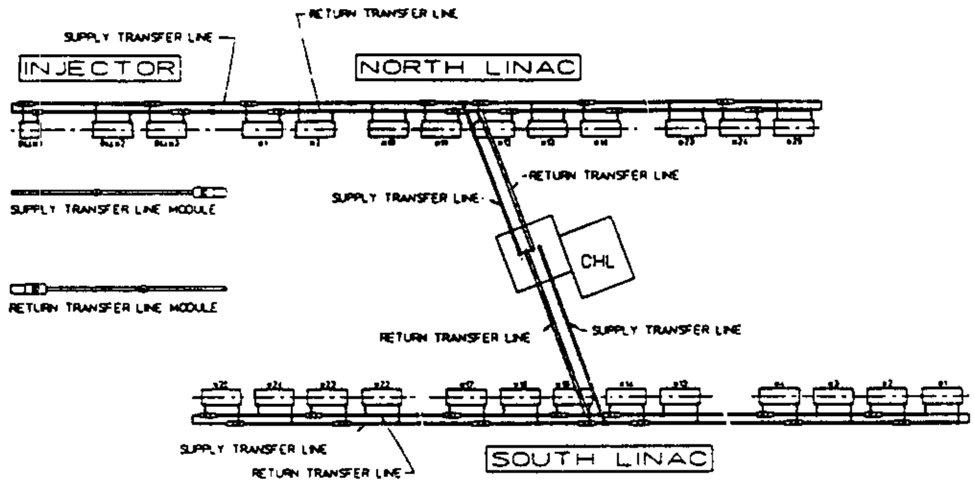

Figure 10: Linac Transfer Line Layout

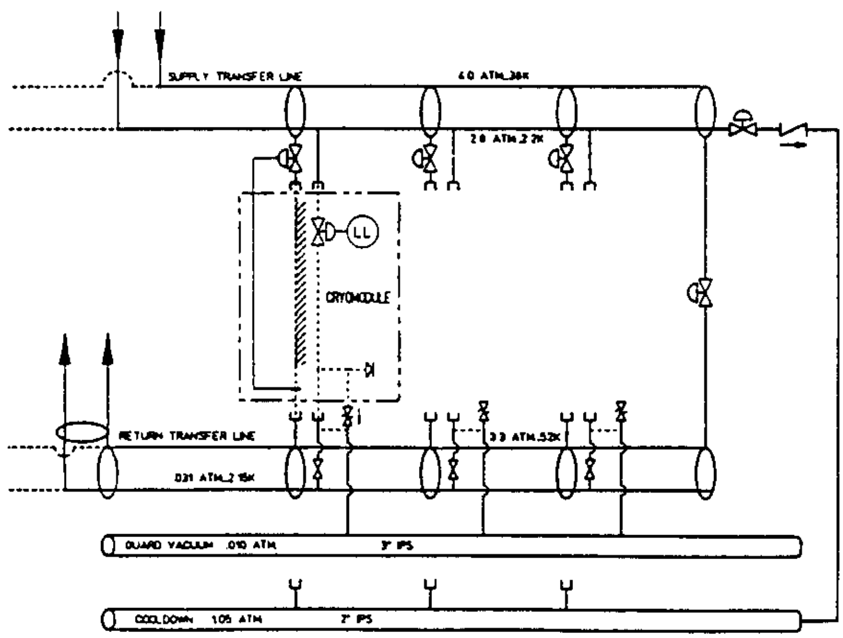

Figure 11: Linac Transfer Line Schematic

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