THE CEBAF CRYOGENIC SYSTEM

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1. 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. The 418 "Cornell/CEBAF" (1) superconducting niobium accelerating cavities are arranged in two 0.5 GeV linacs with magnetic recirculating arcs at each end. There is one recirculating arc (Fig. 1) for each energy beam that is circulating and any three of the four correlated energies may be supplied to any of the three Experimental halls. The recirculating arcs are low field conventional dipoles and quadrupoles. The cavity resonant frequency is 1.5 GHz, each cavity is driven by its own 5kw klystron and the duty factor of the entire system is 100%. (2) (3)

The four hundred accelerating cavities are arranged in pairs in a "cryounit". The ensemble of four cryounits (8 cavities) together with their end caps makes up a complete cryostat called a cryogenic module. The four cryounit helium vessels are cross connected to each other and share a common cryogen supply, radiation shield and insulating vacuum. The detailed design of the cavity and cryostat are more fully described in these proceedings. (4)

The cryogenics system for CEBAF consists of a 5kW central helium refrigerator and a transfer line system to supply 2.2 K 2.8 ATM helium to the cavity cryostats, 40 K helium at 3.5 ATM to the radiation shields and 4.5K helium at 2.8 ATM to the superconducting magnetic spectrometers in the experimental halls. Both the 2.2K and the 4.5K helium are expanded by Joule-Thompson (JT) valves in the individual cryostats yielding 2.0K at .031 ATM and 4.4K at 1.2 ATM respectively. The Central Helium Refrigerator is located in the center of the CEBAF racetrack with the transfer lines located in the linac tunnels.

2. CRYOGENIC SYSTEM LOADS

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 disturbs the superconductive properties. The BCS resistance increases with increasing frequency, and decreases as the operating temperature decreases. Other sources of 2K heat include static heat leak, conduction of heat dissipated in the input waveguide, and absorption of higher-order-mode power generated by the beam current. For CEBAF, an operating temperature near 2.0K is an economic optimum.

The helium refrigeration system at CEBAF must provide an adequate flow of 2K helium to compensate for resistive heating in the niobium and for heat leaks in the cryostat and distribution system. In addition, it must provide helium at 40K to keep heat shields in the cryostat below 50K. Table 1 summarizes the calculated heat losses for CEBAF, assuming an accelerating gradient of 5 MeV/m at a Q of 3×10^9.

TABLE 1

LINAC HEAT LOAD SUMMARY - 418 CAVITIES

	Total Watts	
	2.0K	50K
418-RF Heat Loads		
RF Residual Losses	1337	-
BCS Losses	477	-
Input Waveguides	171	1129
HOM Losses	105	-
Input Waveguide Joint	79	-
Un-Allocated	231	-
Total RF Load	2400	1129
209-CRYOUNIT HEAT LOAD (Inc. Two Half Bridge)		
Radiative (MLI)	46	920
Input Waveguide	263	1714
2 K Supports	19	152
Shield Supports	-	410
Tuner	10	42
Instrumentation	42	84
Un-Allocated	59	105
Sub Total	439	3427
53-PAIR END CAPS (Inc. Set 3 U-Tubes)		
Radiative (MLI)	5	53
JT Valve	13	133
Relief Lines	13	159
Bore Tube	25	366
50K U-Tube Etc.	-	201
2.2K U-Tube Etc.	42	265
2.0K U-Tube Etc.	106	657
Instrumentation	5	10
Supports	3	27
Un-Allocated	25	37
Sub Total	237	1908
TRANSFER LINES		
Supply T. L.	2	80
Return T. L.	17	700
Injector T. L.	2	80
50K U-Tube (5)	-	19
2.2K U-Tube (5)	4	50
Shut Off Valve & Tee (53)	53	424
Junction Boxes (8)	8	80
Refrigerator Connection	38	103
Sub Total	124	1536
Total Static Heat Load	800	6871
GRAND TOTAL	3200	8000
CAPACITY WATT	4800	12,000
%	150%	150%

The CEBAF cryogenics system is designed to handle 150% of the calculated load at 2.0K and 150% at 40K. In addition, superconducting magnets will be used in the experimental spectrometers. These magnets will require helium at 4.4K to handle a cooling load of 154 liters/hour. The option exists to meet this requirement either by purchasing commercially available 4.4K helium refrigerator for the experimental areas, or by designing the central helium refrigerator to handle this additional load; we have chosen the latter due to its lower requirements for operating manpower. Table 2 presents the total cooling requirements (including experimental equipment) for CEBAF's refrigeration plant.

Table 2

Cooling Requirements

	He temp (k)	Calculated load	Refrig. capacity	(%)	Pres. (atm)
Linac cavities	2.0	3200 W	4,800 W	(150)	0.031
Linac heat shields	40.-52.	8000 W	12,000 W	(150)	3.0
End Sta. liquefac.	4.4	154 l/hr	260 l/hr	(169)	1.2

3. OPERATING TEMPERATURE SELECTION

The choice of operating temperature affects the BCS component of the cavity Q and, thereby, the RF heat load, as well as the refrigeration costs (both capital and operating). The BCS losses vary inversely with the cavity Q, approximately doubling every 0.2K. Figure 2 shows 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 increases to the 0.85 power. The net effect is shown in Figure 3.

CEBAF has chosen 2.0K as the operating temperature. The BCS losses, while an exponential function of temperature, are still a small fraction of the total heat load at 2.0K. Figure 3 shows that the refrigeration capital cost is flat to 0.5% between 2.0 and 2.2K. Below 2.0K 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 2.5K (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 2.5K. We have chosen to size the distribution system to be optimized for 2K operation with a flow safety factor of two times the calculated heat load. Since possible future higher cavity gradients will tend to shift the optimum toward lower temperatures, this will permit future beam energy increases without requiring an awkward and costly replacement of the distribution system.

Two-phase helium becomes a superfluid at 2.177K. While we do not expect superfluid problems (vacuum leaks, increased heat leak, or oscillations), we plan to commission the accelerator at a temperature of 2.2 to 2.25K with a few percent higher operating cost. It is our intention to operate at 2.0K after the initial commissioning period.

4. CYCLE DESIGN

The CEBAF refrigeration system is shown in block diagram form in Figure 4 and in schematic form in Figure 5. The primary systems are the screw compressor system, a standard cold box, the 4.4K dewar system, the distribution system, and the cold compressor system. [Table 3, which is keyed to Figure 5, provides a conservative set of process points.]

TABLE 3

CEBAF Refrigerator Process Calculations

Point	Pressure (atm)	Temp. (K)	Enthalpy (J/g)	Flow (g/sec)
0	20.0	300.00	1579.0	1713
0A	20.0	300.00	1579.0	1625
0B	20.0	300.00	1579.0	88
1	20.0	80.00	434.4	1713
1A	20.0	80.00	434.4	1625
1B	20.0	80.00	434.4	88
2	20.0	60.00	329.0	1713
2A	20.0	60.00	329.0	1460
2B	20.0	60.00	329.0	253
3	20.0	38.50	213.8	1460
4	20.0	20.00	108.9	1460
4A	20.0	20.00	108.9	612
4B	20.0	20.00	108.9	848
5	20.0	12.50	61.54	612
6	20.0	9.00	38.25	612
7	2.80	5.61	26.61	612
7 1/2	2.80	5.50	22.53	612
7 1/2A	2.80	5.50	22.53	612
7 1/2B	2.80	4.73	12.73	0
8	2.80	4.50	11.36	612
8A	2.80	4.50	11.36	240
8B	2.80	4.50	11.36	368
8C	2.80	4.50	11.36	4
9	2.80	2.20	5.10	240
9 1/2	.031	2.00	5.10	240
**********	**********	**********	**********	**********
10A	3.0	287.50	1509.0	1101
11	3.0	78.00	420.4	1101
12	3.0	57.69	314.6	1101
12A	3.0	57.72	314.8	986
12B	3.0	57.40	313.1	115
13	3.0	37.49	209.1	986
13A	3.0	37.49	209.1	848
13B	3.0	37.49	209.1	138
13C	3.5	37.49	209.1	115
13D	3.5	37.49	209.1	253
14	3.0	16.39	97.31	848
15	3.0	11.94	72.63	848
**********	**********	**********	**********	**********
20	1.05	287.50	1508.0	608
21	1.08	78.00	420.0	608
22	1.11	57.73	314.6	608
23	1.14	37.50	209.3	608
24	1.16	16.11	97.31	368
25	1.18	12.00	75.41	368
26	1.20	5.23	36.68	368
26A	1.20	5.23	36.68	368
26B	1.20	4.50	30.76	0
27 1/2	1.20	4.424	29.94	368
28	1.20	4.424	11.36	368
**********	**********	**********	**********	**********
34	1.20	23.82	137.9	240
35	0.30	11.45	73.70	240
36	0.10	6.42	47.74	240
38	0.031	3.32	31.72	240
39	0.031	2.15	25.46	240
39 1/2	0.031	2.00	24.65	240
**********	**********	**********	**********	**********
40	1.00	275.00	285.1	267
41	1.20	78.95	-91.8	267

Percent of Carnot = 15.3% with compressor 55% isothermal

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 procurement 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, only applies to the subatmospheric module.

Cold Compressors to achieve the 0.031 ATM operating pressure were chosen for the 2K refrigeration cycle. The warm vacuum pumping compressor solution has two major cost and technological problems:

1. Gigantic Low Pressure Heat Exchangers: These would be state of the art units and most likely require multiple cold boxes.

2. One Mega Watt Vacuum System with Purifiers: Keeping this system leak tight as well as the periodic maintenance will make one year running periods very hard to achieve.

The Cold Compressors, though at the forefront of Helium Refrigeration Technology, are by far the most cost effective solution.(5) There is currently a major world wide effort in this area; four manufacturers have built units: Rota-Flow and Creare in the U.S., and L'Air Liquide and Sulzer in Europe. In addition, there are efforts in System Design and Testing at five major labs: BNL, CEBAF, and FERMILAB in the U.S., CERN and SIN in Europe.

Some additional features worth noting are that the refrigerator may operate as a conventional 1.2-atmosphere, 4.4K helium refrigerator by simply turning off the cold compressors and passing the flow around them. 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 from the 30,000 gal. dewar.

5. THE CRYOGENIC DISTRIBUTION SYSTEM

The distribution system must be sufficiently flexible to allow a wide range of operating conditions. It must be able to handle contingencies, such as the replacement of a cryomodule while maintaining the system in a standby condition. We have selected a solution that provides the required flexibility and also minimizes costs; in addition, it permits the accelerator to operate while a cryomodule is either being warmed up or cooled down. The distribution system operates exclusively with supercritical supplies and JT expansion valves at the loads. The return lines are either vacuum or high pressure gas.

The system depicted in figures 4 and 6 is based upon using the string of cryomodules as part of the supply transfer line, and a transfer line for the return flow. The cryomodules are series-connected in an H" pattern utilizing U-tubes and internal flow to distribute 2.2K helium at 2.8 atmospheres and 40K helium at 3.5 atmospheres. Each cryomodule (Figure 6) is connected to the return cold vacuum line to maintain its 0.031-atmosphere internal pressure, and the shield flow is returned to the transfer line at four places, one at the end of each arm of the H". This series-parallel system minimizes the cost of the distribution system.

If a replacement unit must be removed, the cryomodule containing it would be isolated from the supply by removing the U-tubes at each end of the module. These U-tubes are replaced by a U-tube which spans the gap created by the cryomodule and allows the helium supply to the remaining modules to be resumed in a short time. The cryomodules in the other three arms of the H" are completely unaffected by this operation. Those in the affected arm must rely upon the large helium inventory in each module to maintain the temperature during the very short transition time. The modules upstream of the isolated module may still be supplied with 2K helium, while the downstream modules must rely upon their helium inventory of 1500 liters each to keep cool. The removal and replacement of the U-tubes will not take more than 10 or 15 minutes, which is much less than the several-hour stand-alone capacity of each cryomodule.

In this system, the transfer lines are a simple coaxial design, which can be mass-produced easily and economically (Figure 7).(6) The system will be easy to control, because it has few control valves, each with a well-defined function. A control valve at the end of each branch of the H" will maintain the shield at a temperature between 40K at the inlet and no more than 50K at the outlet. A control valve at each cryomodule will maintain the liquid level in each module in the full state, while the parallel connection to the cold vacuum line will keep the pressure in each module at 0.031 atmosphere for 2K operation.

6. END STATION CRYOGENIC SYSTEM

The design for the CEBAF end stations includes several large superconducting dipoles, quadrupoles, an 8 coil toroid. The dipoles and quadrupoles are assumed to be pool-boiling magnets. These magnets are very simple to control cryogenically, as they need only liquid-level control. The magnets will be cryo-stable, with the exception of the quadrupoles, so that quench detection and protection is reduced to a manageably simple system. The superconducting toroid will be forced cooled and will require an active quench protection system.

The helium system should appear as a utility to the end stations, rather than as an overhead operation with which they must be intimately involved. This concern and the desire to reduce overall system costs suggest that it would be desirable for the central helium refrigerator to provide for this magnet cooling. Thus, supercritical cold gas will be delivered to the end stations and distributed locally via transfer lines.

Each magnet would have a liquid-level control that would run an inlet JT valve. Thus, the problems associated with distribution of liquid helium and two-phase flow will be eliminated. The end station area will have a small compressor and a suction buffer tank to return the warm helium gas from the magnets through a small high-pressure line. The gas will pass through the nitrogen-cooled utility purifier before entering the central refrigerator. Table 4 summarizes the end station magnets.

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4. G. Biallas, et. al., The CEBAF Cavity Cryostat, Linac 86.

5. A. P. Schlafke, et. al., Combined Cold Compressor/Ejector Helium Refrigeration Cycles Adv. In Cryogenic Eng., Vol. 29, 1983, P. 487.

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TABLE 4

END STATION MAGNETS

Spectrometer	Qty	Type	Lead Flow	5K Load	80K Load
End Station A					
4 GeV/c	(2)	dipole	6 l/hr	8 l/hr	2 l/hr
	(4)	quad	12 l/hr	28 l/hr	4 l/hr
1.2 GeV/c	(2)	dipole	6 l/hr	8 l/hr	2 l/hr
	(2)	quad	6 l/hr	14 l/hr	2 l/hr
End Station B					
Toroidal	(1)	Toroid (Plus 5 g/sec 300k He)	6 l/hr	12 l/hr	10 l/hr
End Station C					
4 GeV/c	(4)	dipole	12 l/hr	16 l/hr	4 l/hr
	(2)	quad	6 l/hr	14 l/hr	2 l/hr
			54 l/hr	100 l/hr	26 l/hr nitrogen

Design Load 154 l/hr
Refrigerator Capacity 260 l/hr (169%)

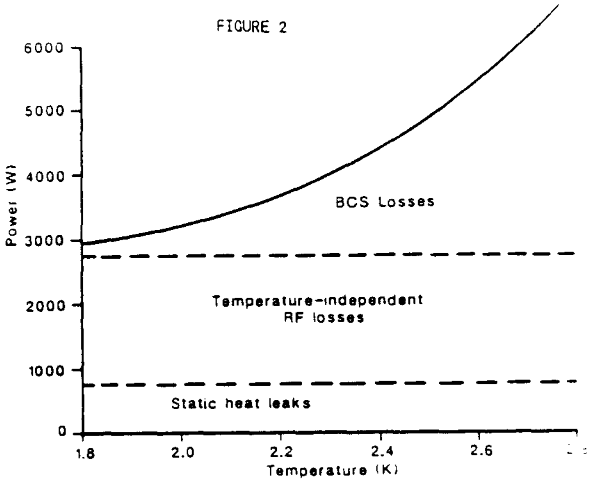


FIGURE 2

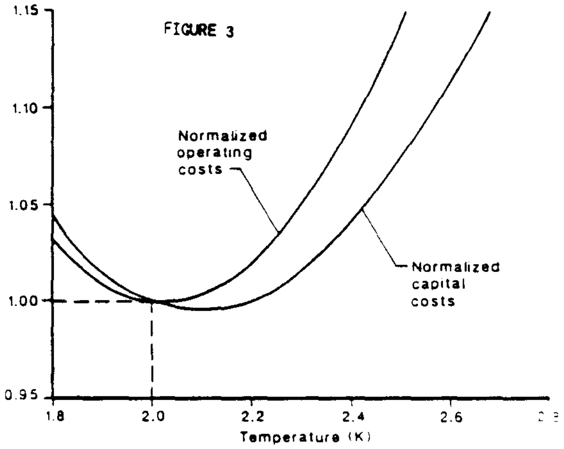


FIGURE 3

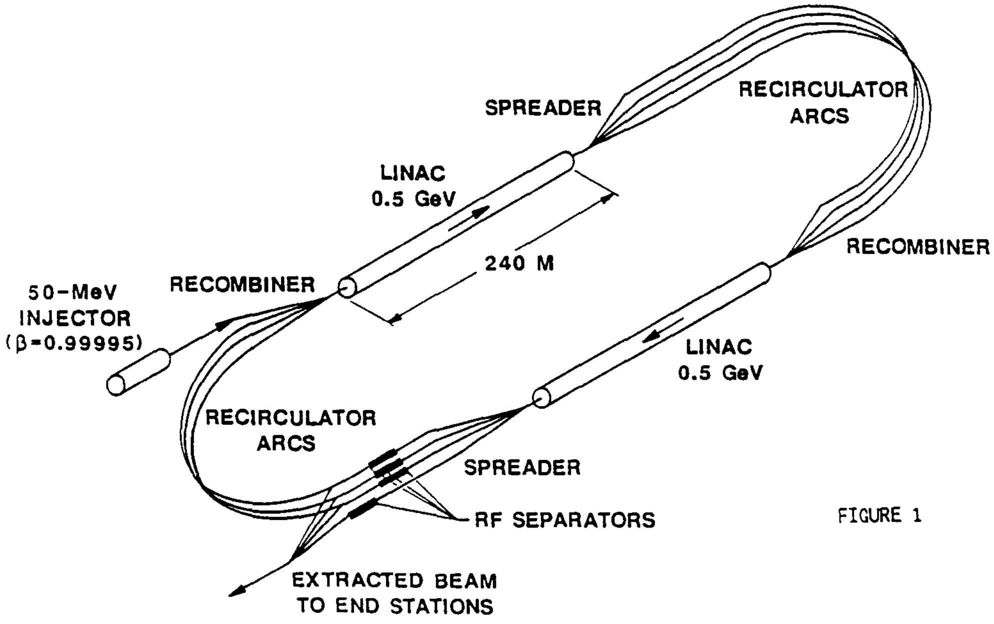


FIGURE 1

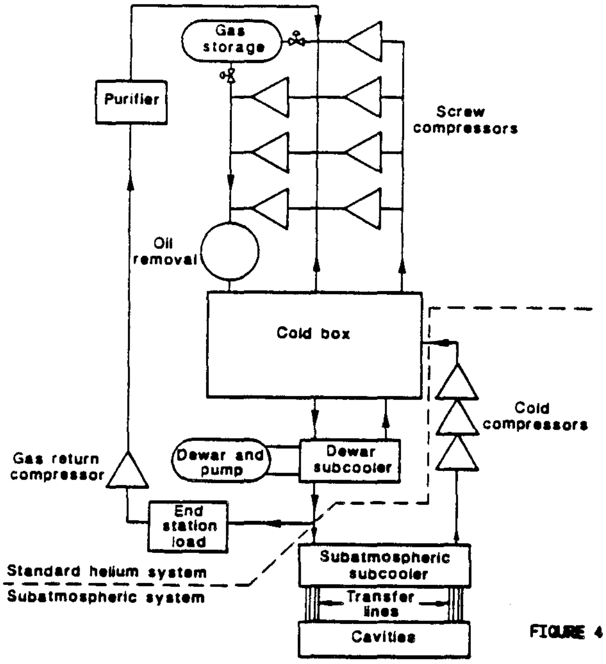
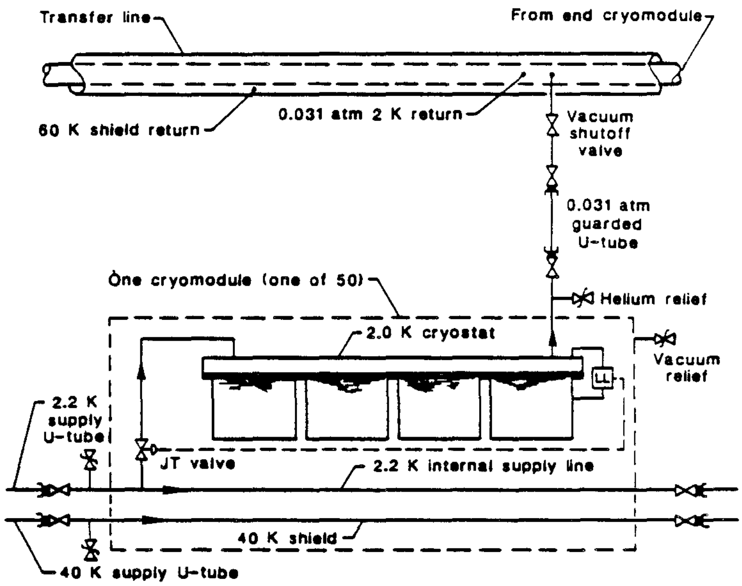


FIGURE 4

FIGURE 6



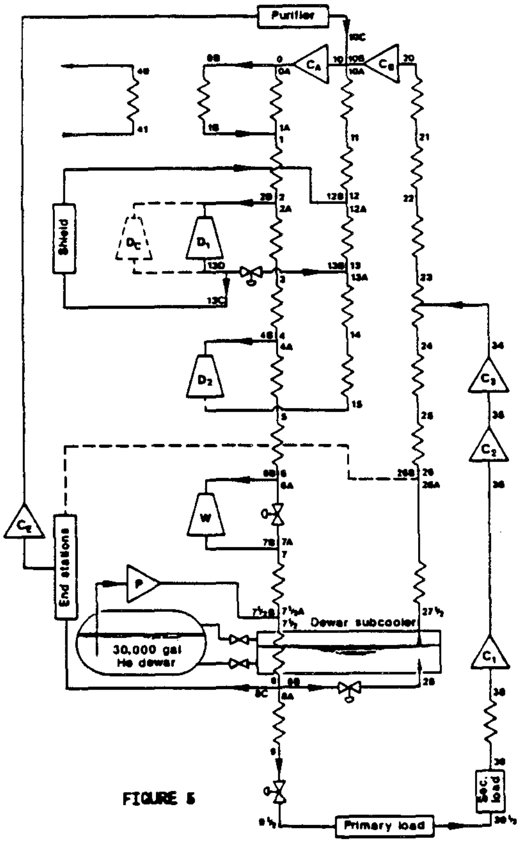


FIGURE 5

FIGURE 7