4. REFRIGERATION

4.1 Description of the Refrigeration System

Refrigeration is provided by a central plant (the CHL) with nitrogen and helium liquefiers and 24 satellite refrigerators in service buildings. This arrangement combines advantages of a single central facility with those of individual stand-alone units stationed around the ring. The central liquefiers have the high efficiency associated with large components, but requirements for distribution of cryogenic liquids and electric power to the service buildings are reduced. The likelihood of continued operation in the event of equipment failure is also significantly improved.

The total power to run the system is 11.33 MW. This provides 2,550 ℓ/h of liquid nitrogen, which in turn is used in the liquefaction of 4,000 ℓ/h of 4.6 K helium. The helium is then used in the 23 kW of 4.6 K refrigeration produced by the satellites.

The nitrogen reliquefier produces liquid into a 14,000-gallon dewar which supplies the needs of the CHL, the satellite system and the magnet shields. It operates in a closed cycle, collecting warm nitrogen gas from the magnet shields, the transfer lines, the helium cold box, purifiers, and satellites. The liquid is transported in vacuum-insulated transfer lines from the dewars to all use points.

Liquid helium from the central liquefier is collected in a 5000-gallon dewar and pumped through the feed line to each of the 24 satellites and subsequently distributed to the ring. Each satellite uses 144 ℓ/h for lead cooling and satellite "boosting." The boosting action results in 966 W of 4.6 K refrigeration being delivered to the magnet string. In this process, the liquid from the CHL is warmed to ambient temperature and recompressed for delivery back to the CHL and use in the high-pressure stream to the cold box. This system has the advantage of extracting the available refrigeration from the stream at each satellite location, reducing the size and cost of the necessary transfer lines.

Figures 4-1 and 4-2 show schematically the major components of the helium-refrigeration system. Figure 4-1 on page 65 shows the components located at the central helium-liquefaction facility. These are:

a) Two parallel helium compressors A and B.

b) A single oil-removal system C serving both compressors.

c) A medium pressure helium gas storage facility D which removes or adds gas to the system upon demand.

d) A compressor-seal gas-cleanup system E to repurify helium gas leaking from the compressor piston-rod packings.

e) The helium-liquefier cold box F.

f) A liquid-gaseous helium separator G in which the gas of the liquefier JT stream is separated from the liquid and returned to the liquefier.

g) A 5,000-gallon liquid-helium storage tank H.

h) A liquid-helium pump I followed by a subcooler to drive liquid helium from the CHL to the distribution system.

Figure 4-2 on page 66 shows the major components of one of the 24 satellite stations along the ring. Liquid helium circulates through the distribution line, which parallels the magnet ring. Excess liquid is returned to the storage dewar H of Fig. 4-1. Each satellite station refrigerator cold box M requires liquid in an amount sufficiently large to cool two strings of magnets. Liquid from M flows to the magnet string through a subcooler L. At the end of each magnet string the pressure of the

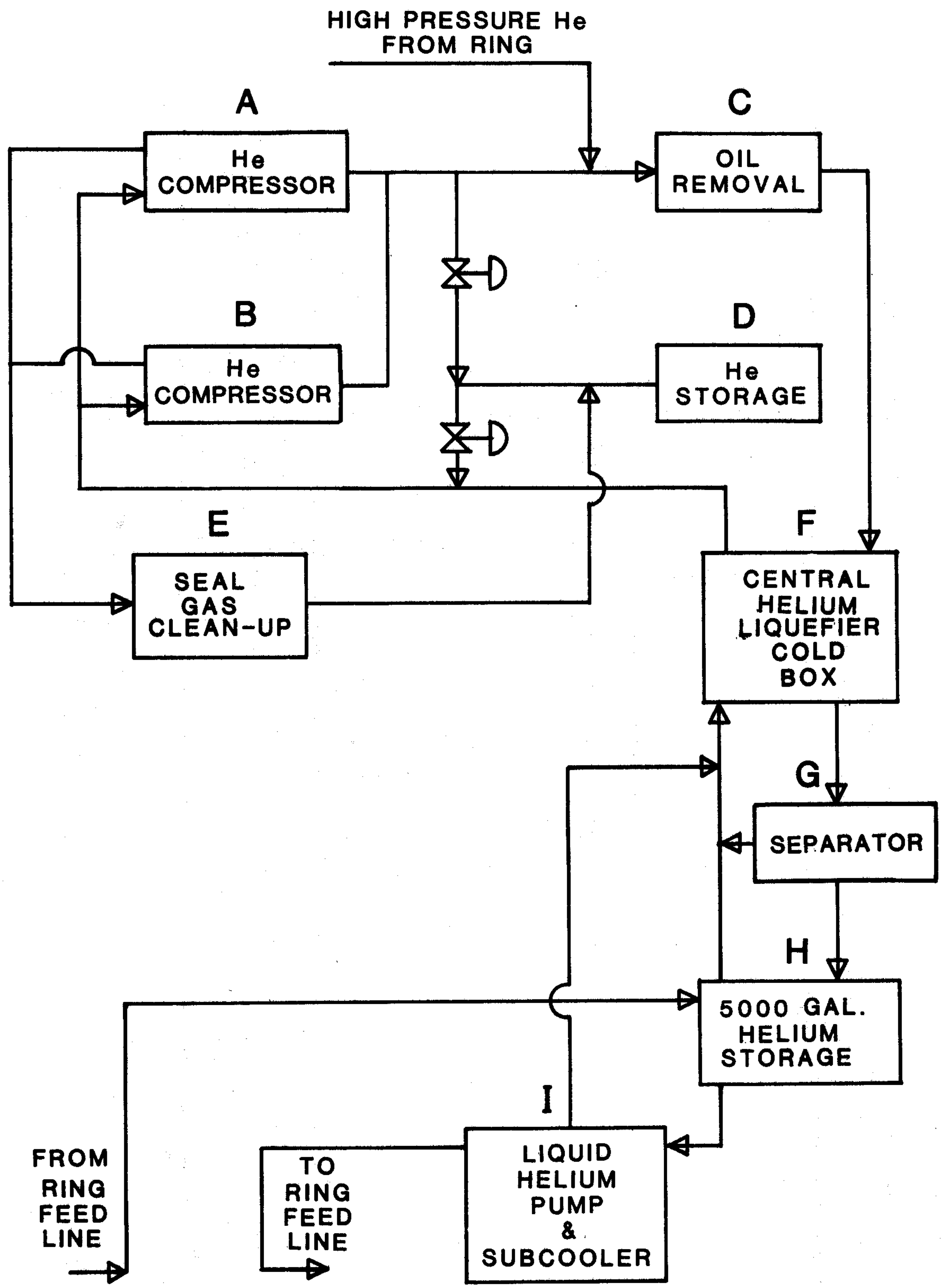


Fig. 4-1. Central helium liquefier.

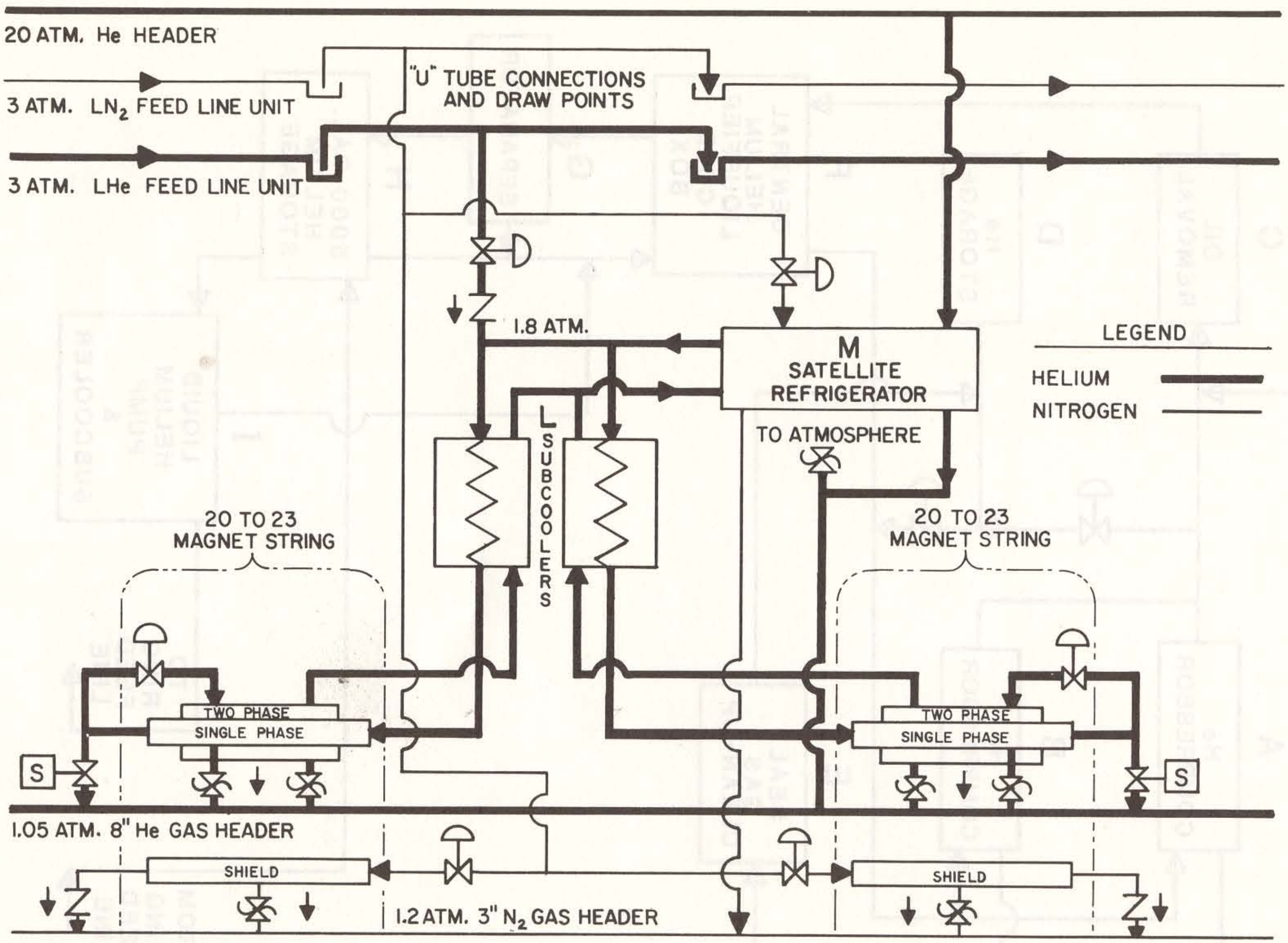


Fig. 4-2. Satellite refrigerator.

single-phase liquid is dropped in a JT valve and it is returned as two-phase liquid. This two-phase fluid cools the magnets and is returned to the satellite-refrigerator cold box M, after passing through the low-pressure side of the subcooler L.

An overall layout of the helium refrigerator system is shown in Fig. 4-3 on page 68, illustrating the relative location of the major refrigeration components, helium-transfer line and warm piping. Compressors of the satellite refrigerator are located in six service buildings along the ring. Low- and high-pressure gas is distributed through 8-in. and 3-in. pipes, respectively. The 8-in. pipe also serves to receive the low-pressure gas flow from the electrical leads and cooldown flow during the time when the ring is cooled from ambient temperature. Helium gas is returned to the CHL after compression by the satellite refrigerator compressors through the 3-in. high-pressure header.

4.2 System Requirements

The static heat load of a dipole magnet has been measured to be approximately 7 W at 4.6 K. AC eddy current and hysteresis losses are approximately 450 J per magnetic cycle. Quadrupole-package heat loads at 4.6 K are estimated to be approximately equal to those of a dipole. Tables 4-I and 4-II list the calculated load for the dipole and quadrupole magnets. The dipole numbers differ slightly from those measured from a string of magnets.

Each of the 24 satellite refrigerators supply subcooled single phase helium to typically 32 dipoles and 8 quadrupoles in the two parallel

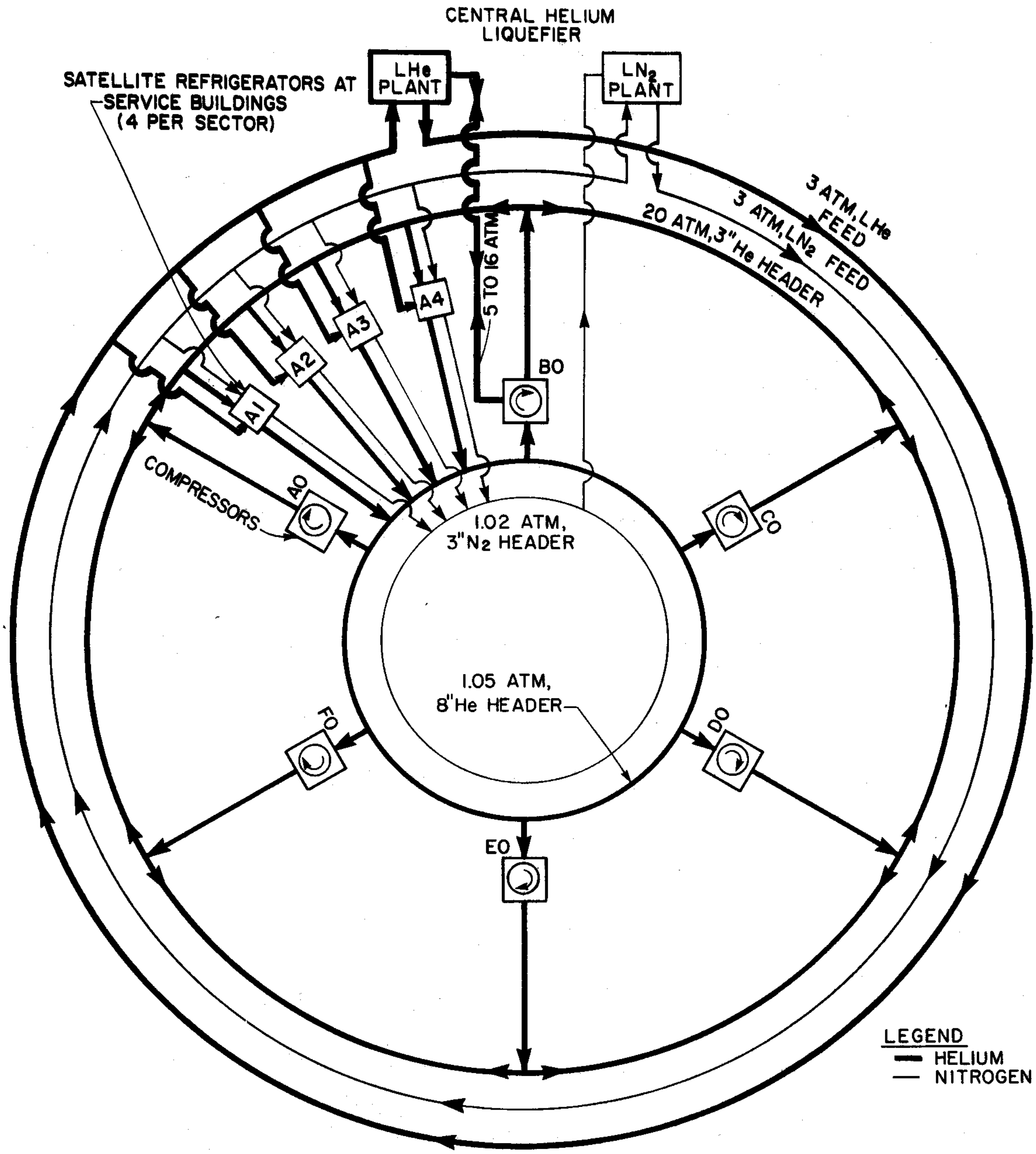


Fig. 4-3. Layout of the refrigeration system.

Table 4-I. Calculated Dipole Heat Loads.

Dipole Model 135 Cryostat	80 K W	4 K W
Infrared (main body)	10.08	0.381
Supports conduction	13.30	3.028
Anchor	1.00	0.164
Vent pipe (Mark 1 Model)	1.66	0.108
Instrumentation leads		0.156
Infrared (junction)	0.38	0.155
4 K cooling	-3.99	
Totals	22.43 W	3.992 W

Table 4-II. Calculated Quadrupole Heat Loads.

Quadrupole	80 K W	4 K W	Evap. ℓ/h
Infrared (main body)	6.41	0.210	
Infrared (junction)	0.19	0.008	
Supports conduction	3.04	0.680	
4 K cooling	-0.90		
Vent pipe for LN_2	0.27		
Vent pipe for 1ø	1.91	0.496	
Vent pipe for 2ø	1.57	0.325	
1 safety lead (5 kA)		1.000	
5 pairs of correction leads (75 A)		0.75	1.05
Instrumentation leads		0.156	
Totals	12.49 W	3.63 W	1.05 ℓ/h

cryogenic loops. The heat deposited in the liquid is exchanged with the return two-phase counterflow helium. The entire helium system is shielded by a two-phase nitrogen system. These systems are labeled in the dipole cross section of Fig. 3-1 on page 33. Table 4-III gives the distribution of loops in a sector with the location of the feed and turn-around points and the number of magnets per loop. Table 4-IV gives the heat loads and refrigeration and helium requirements of a worst-case

Table 4-III. Magnet Cooling Loops.

		Four Satellites per Sector				
Building	Feed Station	Turn-Around Station	Loop	Dipoles	Quads	Special Quads
1	15	11	1	16	3	3
		21	2	18	5	-
				34	8	3
2	25	21	3	16	4	-
		29	4	16	4	-
				32	8	-
3	35	29	5	16	4	-
		39	6	16	4	-
				32	8	-
4	45	39	7	16	4	-
		49	8	15	2	3
				31	6	3
Totals				129	30	6

Table 4-IVa. 4.6 K Refrigeration Loads (Worst Building).

	Each		1000 GeV DC		1000 GeV 35 s cycle	
	W	ℓ/h	W	ℓ/h	W	ℓ/h
34 dipole magnets	7.0	-	238.0	-	238.0	-
34 dipole ac losses[a]	13.0	-	-	-	442.0	-
11 quad magnets	7.0	1.05	77.0	11.55	77.0	11.55
11 quad ac losses[a]	11.0	-	-	-	121.0	-
1 pair 5000-A leads[b]	10.0	14.0	10.0	14.0	10.0	14.0
Set end boxes	20.0	-	20.0	-	20.0	-
Totals			345.0 W	25.55ℓ/h	908..0 W	25.55 ℓ/h

[a]35-s cycle time
[b]7 out of 24 buildings

Table 4-IVb. 80 K Nitrogen Requirements (Worst Building).

	Each	1000 GeV DC	1000 GeV 35-s Cycle
	W	W	W
34 dipole magnets	22.4	762	762
11 quadrupole magnets	13.5	138	138
Totals		900	900

service building. In the standard mode of operation the satellite refrigerator uses liquid helium from the Central Helium Liquefier to produce the necessary refrigeration in a building. In addition, the CHL must supply the liquid for the power leads. Specifications for the satellite are given in Table 4-Va and b and those for the Central Helium Liquefier and Nitrogen Reliquefier in Tables 4-VI and Table 4-VII respectively, shown immediately following.

Table 4-Va. Satellite-Refrigerator Parameters.

Mode	Consumption	Production
Satellite	129 ℓ/h He	966 W
Refrigerator	52 ℓ/h N_2	623 W
Liquefier	84 ℓ/h N_2	126 ℓ/h He
Accelerator standby	59 ℓ/h N_2	490 W + 26.6 ℓ/h He

Table 4-Vb. Mycom Satellite-Compressor Parameters.

Type	Screw
Stages	2
Power	350/261 Bhp/kW
Suction pressure	1.05 atm
Discharge pressure	20 atm
Throughput	57.54 g/s

Table 4-VI. Central Helium Liquefier Specification.

Inlet pressure	1.05 atm
Discharge pressure	12.3 atm
Flow rate (two compressors)	8,573 lb/h
Power required (two compressors)	2,470 kW
Power required (He air cooler)	52 kW
Liquid helium production (9,900 lb/h of He at 11.9 atm to the cold box)	≥ 4,000 ℓ/h at 4.6 K
Liquid nitrogen consumption per liter of liquid He produced	≤ 0.6 ℓ/ℓ

Table 4-VII. Nitrogen Reliquefier Specifications.

Nitrogen reliquefier	2,550 ℓ/h 54 tons/day
Production rate based on	
a compressor flow rate of	37,500 lb/h
suction pressure	1.05 atm
discharge pressure	123.5 atm
power requirement	2,540 kW

A summary of the total system requirements, consumption, and production specifications is given in Table 4-VIII, together with power requirements.

Table 4-VIII. Summary of Refrigeration Requirements. and Production Figures

	1000 GeV, dc		1000 GeV, 35-s cycle	
Requirements	W	ℓ/h	W	ℓ/h
Helium				
Magnet system helium, 4.6K	7,480	350	19,918	350
Helium transfer line pump, 4.6 K	200		200	
Satellite consumption		≃1,548		3,096
Total	7,680 W	≃1,898 ℓ/h	20,118 W	3,446 ℓ/h
	W	Equiv. ℓ/h	W	Equiv. ℓ/h
Nitrogen				
Magnet system nitrogen, 80 K	21,600	490	21,600	490
Helium transfer line	4,500	100	4,500	100
CHL at 3,446 ℓ/h				2,068
Total at 3,446 ℓ/h He				2,658 ℓ/h
Total at max. operation				3,590 ℓ/h
Power		kW		
24 satellites		6,270		
Central Helium Liquefier		2,552		
Nitrogen Reliquefier		2,540		
Total		11,332 kW		
Production	W		ℓ/h	
Helium				
Satellite refrigerators	23,000			
Central Helium Liquefier	200		≥4000	
Nitrogen				
Reliquefier (Additional liquid nitrogen can be purchased at approximately $140 for 2400 ℓ)			2,550	

4.3 Central Helium Liquefier

The central liquefier consists of three large compressors, a helium liquefier, nitrogen liquefier, purification equipment, and storage tanks. The compressors are surplus compressors from an air-separation plant. Two of the three have been modified for helium service, while the third will operate for nitrogen service. Nitrogen production is rated at 2550 ℓ/h. The liquid helium is fed from the storage dewar to a pump dewar, where it is compressed from 1.4 to 3.0 atm. The flow is then cooled to 4.65 K by heat exchange with liquid in the pump dewar. The dewar boil-off is returned to the liquefier as 5 K gas. The 4.65 K, 3-atm output of the exchanger feeds the ring transfer line.

4.4 Satellite Refrigerators

Each unit consists of a 35-ft long heat-exchanger column, a liquid expansion engine, two flow-splitting subcoolers, and a stand-by 30 K gas expansion engine. The unit has four modes of operation, as illustrated in Table 4-Va and shown schematically in Fig. 4-4. The primary mode, which will be used for the accelerator operation, is the satellite mode. The unit is continuously supplied 4.48 g/s liquid helium (plus 0.5 g/s power-lead flow) from the CHL. This causes an imbalance in the heat-exchanger flow (53.06 g/s supply vs 57.54 g/s return) giving a double pinch at 25 K and 5 K. The liquid engine expands from 20 atm to 1.8 atm, producing slightly subcooled liquid. The cold-end refrigeration comes from three sources: 44% from the heat exchangers flow imbalance, 48% from the liquid expander, and 8% from the central liquefier flow.

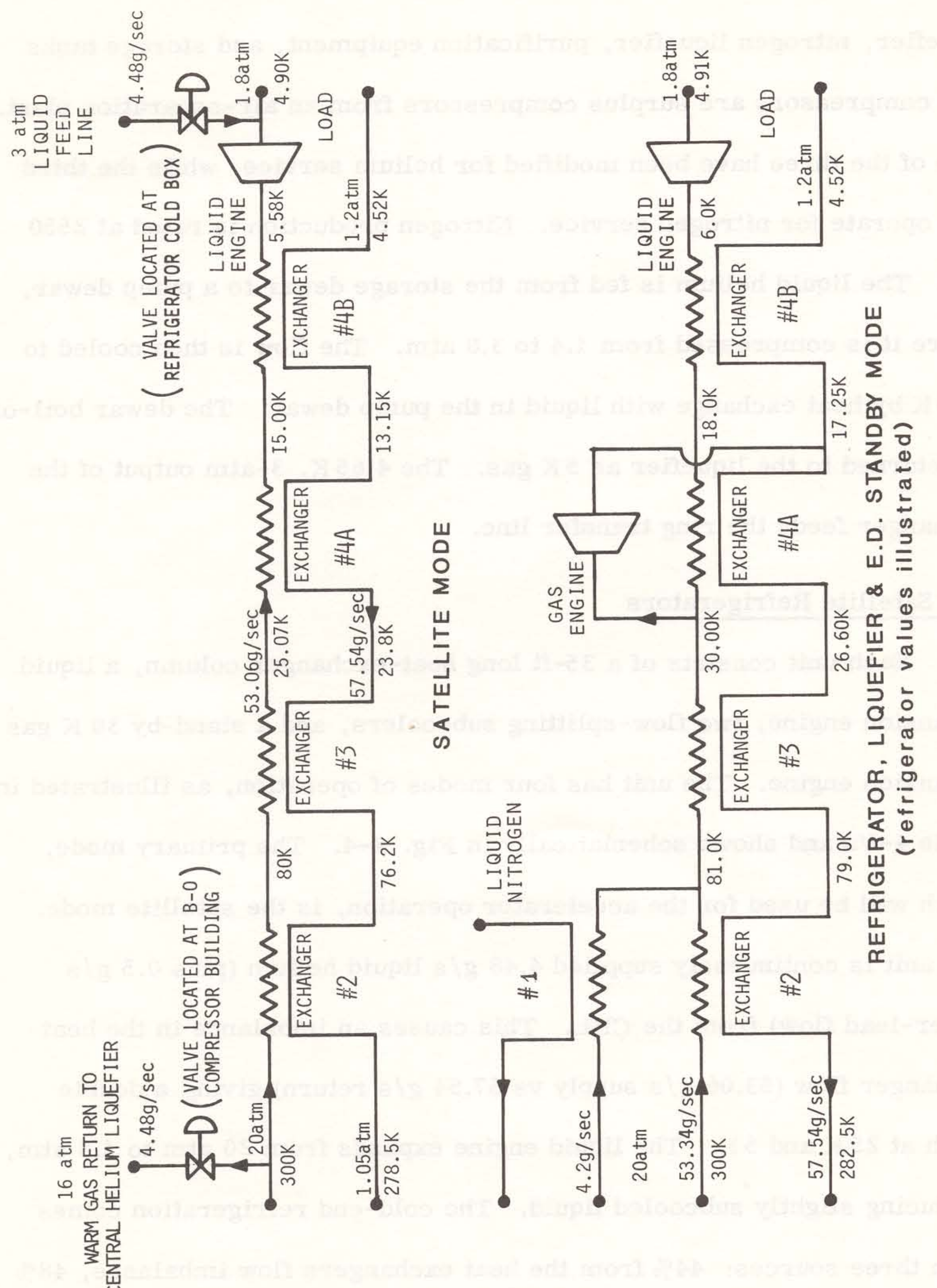


Fig. 4-4. Satellite refrigerator modes.

In the other three modes, liquid nitrogen is used instead of liquid helium. The stand-by gas engine is now operated at 30 K for these modes, while the liquid engine produces a two-phase liquid-gas mixture. We have tested the cold box and expanders in the first three modes and exceeded design in both the liquefier and refrigerator modes and 90% of design in the first attempt in the satellite mode. The stand-by mode is a mixture of refrigeration modes and liquification with a trade-off ratio of 5.0 W to 1.0 ℓ/h. This mode is designed to cool strings of magnets without the aid of the CHL both during initial construction and later during failures of the CHL. This mode was used for both the 10- and 25-magnet A1 runs. There are many additional mixtures of satellite and refrigeration modes that could be used if the CHL were operating at reduced efficiency.

4.5 Feed System

The liquid He and N_2 will be fed to the ring by a 25-section, 4-mile long vacuum-jacketed loop. The loop runs from the CHL to A4, around the ring in the proton-beam direction to A3 and then back to the CHL. The N_2 that is used to cool the shields of the magnets also provides the shield for the feed line. The sections are coupled by two rigid vacuum-jacketed U-tubes, each with a branch tee to feed the local satellite refrigerator. This will permit us to install, test, and cool down one section at a time without interfering with the operation of the rest of the system. With the connection of the last service building, A3, back to the CHL, we can take any section out of service for repair, if needed, by feeding the return line in reverse. We estimate a maximum 4.6 K heat load of 150 W and maximum 80 K load of 4500 W for the entire line.

The satellite gas piping consists of three gas header loops. On the wall of the tunnel behind the magnet, there is an 8-in. low-pressure He pipe and a 3-in. low-pressure N_2 pipe. The He pipe is the suction line for the compressors, as well as the main magnet relief and manifold for lead and cooldown flow. The N_2 pipe is the collection header for all shield flow, precooler flow, and also N_2 reliefs. The third header is a high-pressure He pipe that is located on the Main Ring road side of the berm. These are shown in plan in Fig. 4-3 and in elevation in Fig. 4-5 and Fig. 1-1.

Two 3-in. gas headers which connect to the CHL are located at A4. The first is a 10- to 18-atm bidirectional He gas line. Normally it is used as the gas return for the liquid supplied by the CHL, dumping gas into the discharge of the CHL compressors (13 atm). During startup and in accelerator standby mode, the line can also supply gas to the 8-in. header. The second header is teed into the 3-in. N_2 loop and is the main N_2 return for the N_2 liquefier.

The compressor system is located in the six "zero" buildings, with four compressors per building for maximum capacity. The compressors are connected across the two He headers with all twenty-four in parallel. The grouping of compressors into a header system totally decouples cold boxes from compressor operation; that is, we can shut down all four compressors at B0 without shutting down any cold boxes (but of course we have lost 1/6 of our total capacity).

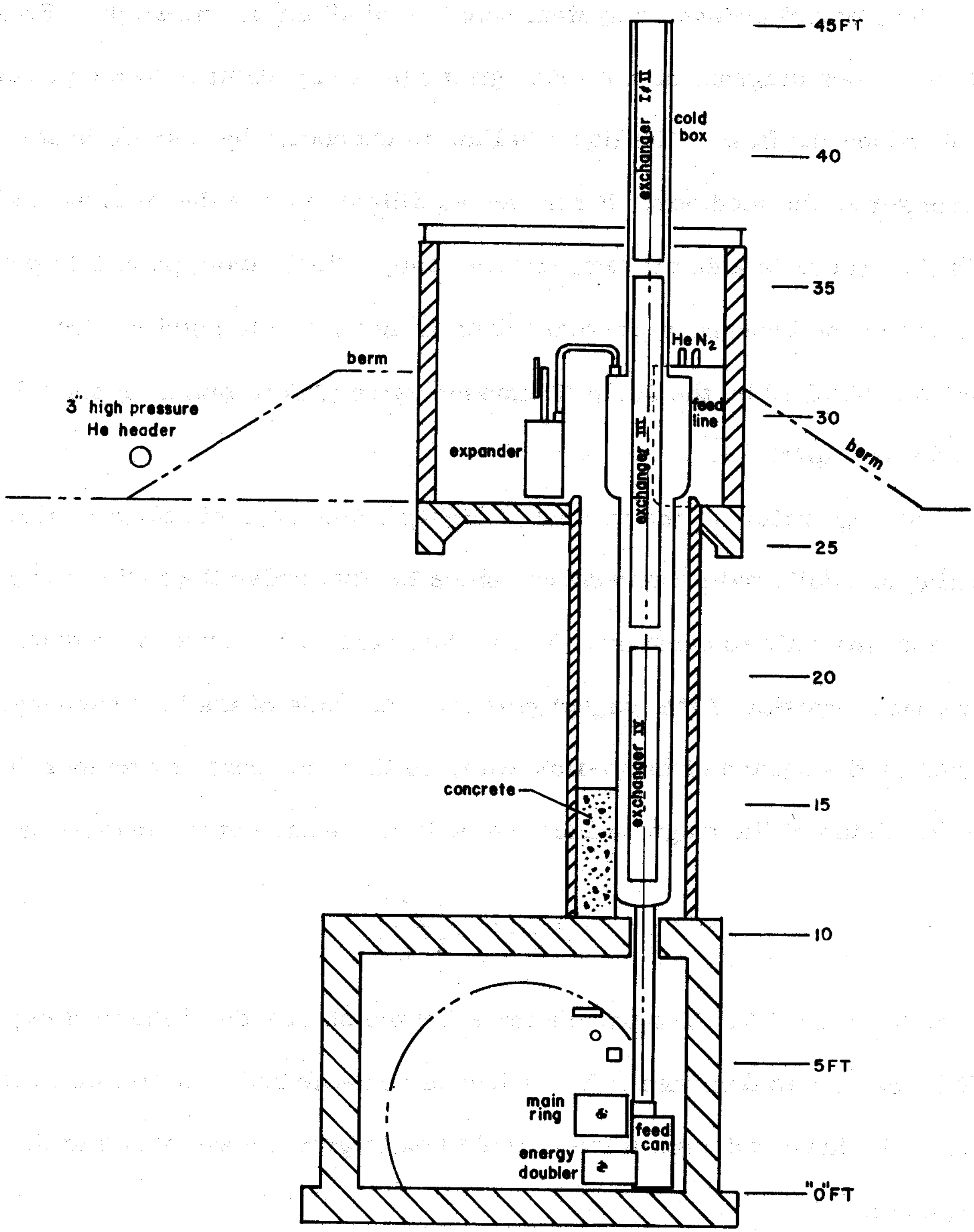


Fig. 4-5. Cross section of satellite refrigerator and cryogenic feed to the superconducting magnets in the tunnel.

4.6 Tunnel Components

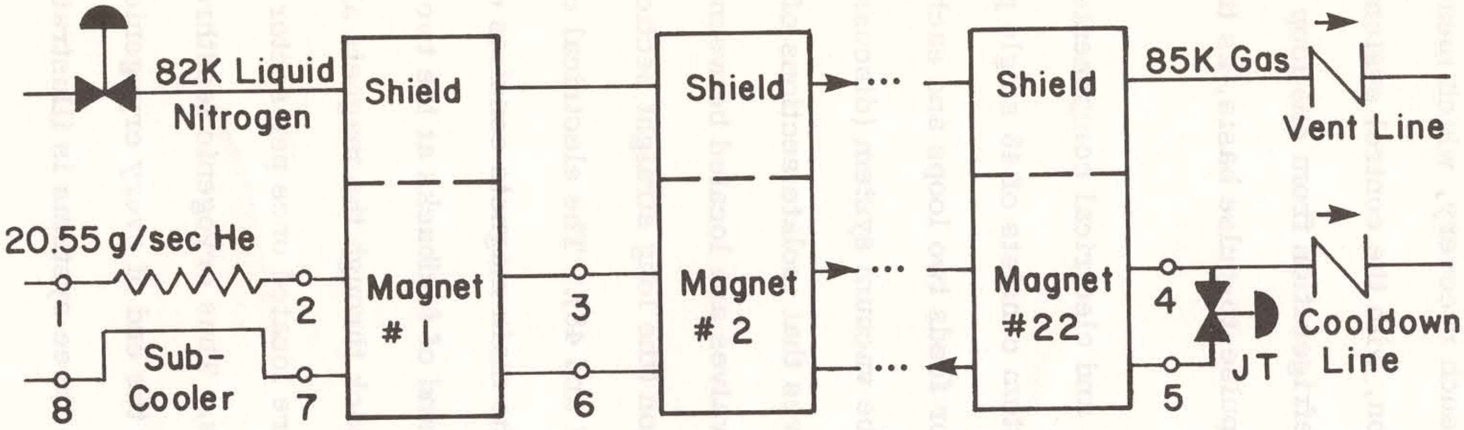
The tunnel cryogenic system consists of 48 cryogenic loops. Figure 4-6 is a block diagram of one loop, giving the temperatures at significant points along the flow. The liquid helium is subcooled by a small heat exchanger in the feed box. It reaches equilibrium after the first magnet, at point 3. There is a small temperature rise, 0.05 K, from point 3 to point 4 because of the two-phase pressure drop from point 5 to point 6. The flow is controlled by the Joule-Thompson valve (JT) to maintain point 8 at 0.1 K of superheat.

The operation of the system at higher capacity is simply a matter of turning on additional compressors, since to first order the ratio of capacity to mass flow rate is constant. It must be noted that the pressure drop in the two-phase cryostat of the magnet plus the shell side of the heat exchanger varies as the square of mass-flow rate, so that the operating temperature of the shell side of the magnets increase with the square of the mass-flow rate.

$$T = T_0 + \alpha\left(\frac{F}{F_0}\right)^2 ,$$

where $T_0 = 4.277$ K. The parameter α for the shell side of the prototype refrigerator was designed to be as low as possible and was measured to be 0.4 K. We have redesigned the A2 cold box to give a lower value of this parameter.

The extreme importance of α as a design parameter is not generally appreciated. Commercial refrigerators give 0.3 to 0.4 K, but we have been trying to reach less than 0.2 K. Not only does a low α mean that one can



POINT	T(K)	P_{atm}	$H_{J/g}$	% LIQUID
1	4.90	1.8	14.22	100.
2	4.50	1.8	11.20	100.
3	4.55	1.8	11.47	100.
4	4.60	1.8	11.75	100.
5	4.47	1.25	11.75	96.
6	4.42	1.2	27.49	13.
7	4.42	1.2	27.99	10.
8	4.52	1.2	31.01	0.1K Super Heat

Fig. 4-6. Details of the cooling loop for a string of cryogenic magnets (1/48 of the ring).

operate at lower temperatures and, conversely, higher capacities in special areas (low beta, extraction, and injection), but also that one can operate at twice nominal capacity during quench recovery, which means a factor of 3 to 5 in recovery time. In addition, with the control system as installed at A2 we can automatically shift refrigeration from one loop to another or from one sector to another on a pulse-to-pulse basis, as the beam scrapes at different locations.

The main magnet cryogenic, vacuum, and electrical components are unavoidably interwoven. The cryogenic system consists of 48 single phase-two phase loops. Each satellite refrigerator feeds two loops and each loop has a JT valve at its far end. The beam-tube vacuum system (discussed in more detail in Section 5) has warm gate valves that isolate sections of each sector at (typically) ten locations. These valves are located between cryo loops and at the two ends of each warm region (the long straight section and the medium straight sections at locations 17 and 48). The electrical circuit (discussed in more detail in Section 6) for the main magnets consists of all coils connected in series along the coil bus and of foldbacks at the two ends of the B0 straight section bringing current back through the magnets along the return bus. Power-supply feed points are located once per sector at the same locations as one of the cryogenic feeds. Thus cryogenic feedthroughs of the two electrical buses are necessary at the end of every cryogenic loop except at B0. The interrelation between the three systems is illustrated for a typical sector in Fig. 4-7.

The feed box contains a pair of power leads where necessary, one or two cryogenic feedthroughs, a pair of subcoolers and instrumentation for

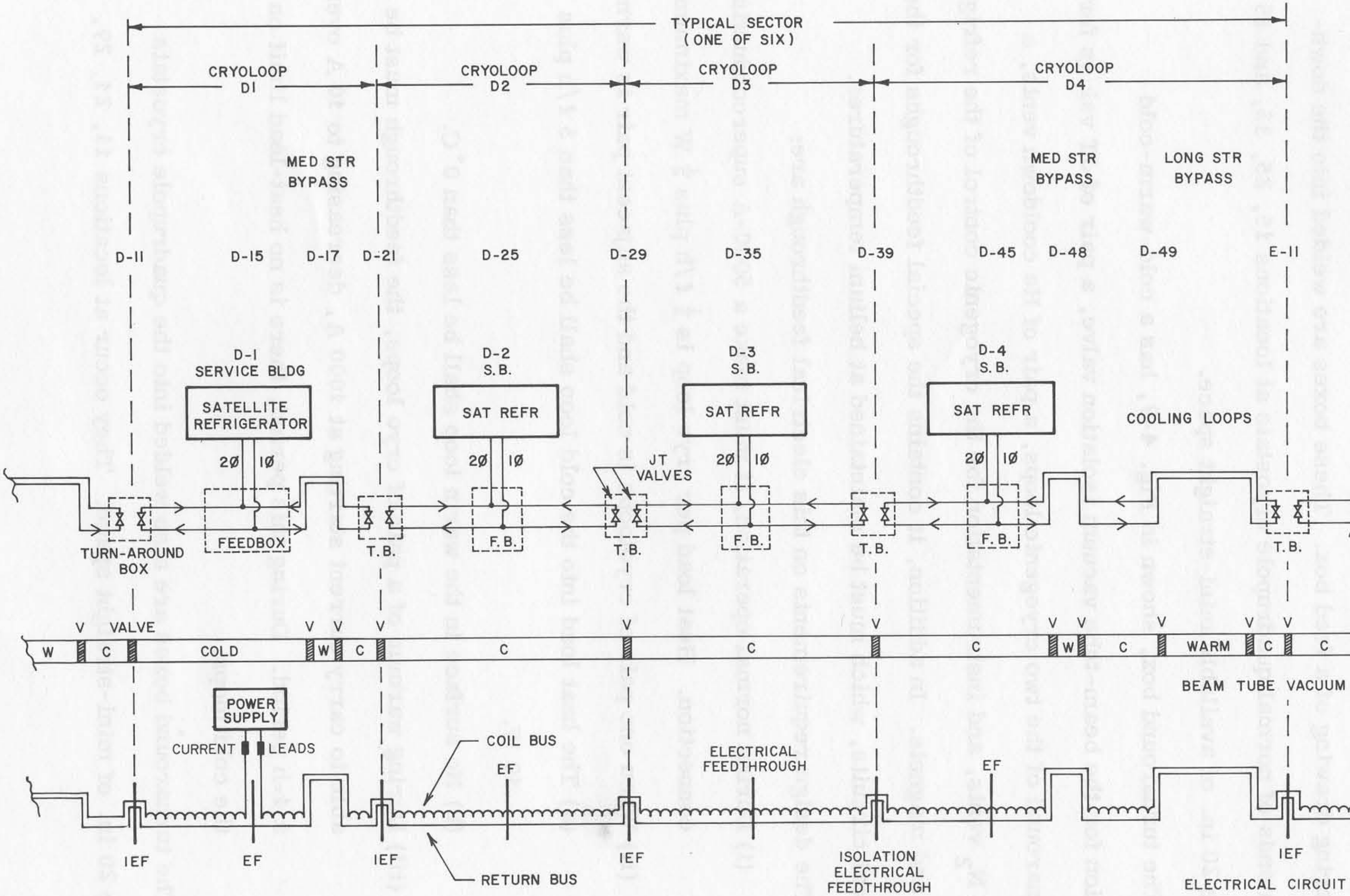


Fig. 4-7. Schematic of cryogenic components in the tunnel for a typical sector.

cryogenic control of the refrigerator and magnets. Figure 4-8 is a simplified engineering drawing of a feed box. These boxes are welded into the downstream ends of normal quadrupole cryostats at locations 15, 25, 35, and 45 and use 20 in. of available mini-straight space.

The turnaround box, shown in Fig. 4-9, has a cold-warm-cold transition for the beam-tube vacuum isolation valve, a pair of JT values for the turnaround of the two cryogenic loops, a pair of He cooldown vents, a pair of N_2 vents, and instrumentation for the cryogenic control of the refrigerator and magnets. In addition, it contains the special feedthroughs for the electrical circuits, which must be maintained at helium temperatures.

The design requirements on this electrical feedthrough are:

(i) During normal operation, it must make a 5000-A superconducting connection. Heat load per cryo loop is $\frac{1}{2}$ ℓ/h plus $\frac{1}{2}$ W maximum.

(ii) When one pair of cryoloops is cold and the adjacent pair is warm:

(a) The heat load into the cold loop shall be less than 5 ℓ/h plus 10 W.

(b) No surface in the warm loop shall be less than 0°C.

(iii) During warmup of a pair of cryo loops, the feedthrough must be able to carry current starting at 1000 A, decreasing to 10 A over a 4-h period. During this period, there is no heat-load limit on the cold loops.

The turnaround boxes are also welded into the quadrupole cryostats and use 20 in. of mini-straight space. They occur at locations 11, 21, 29, and 39.

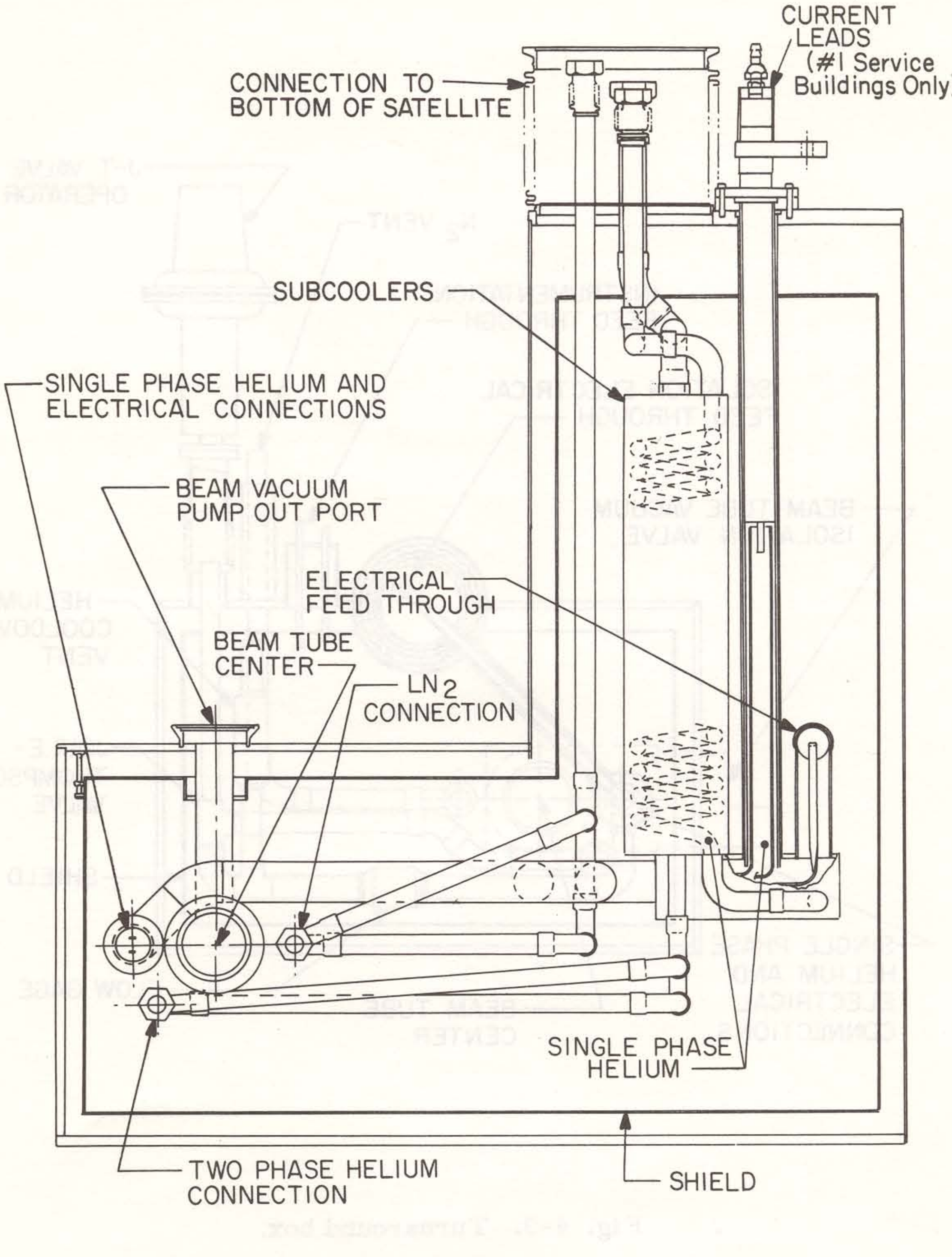


Fig. 4-8. Feed box.

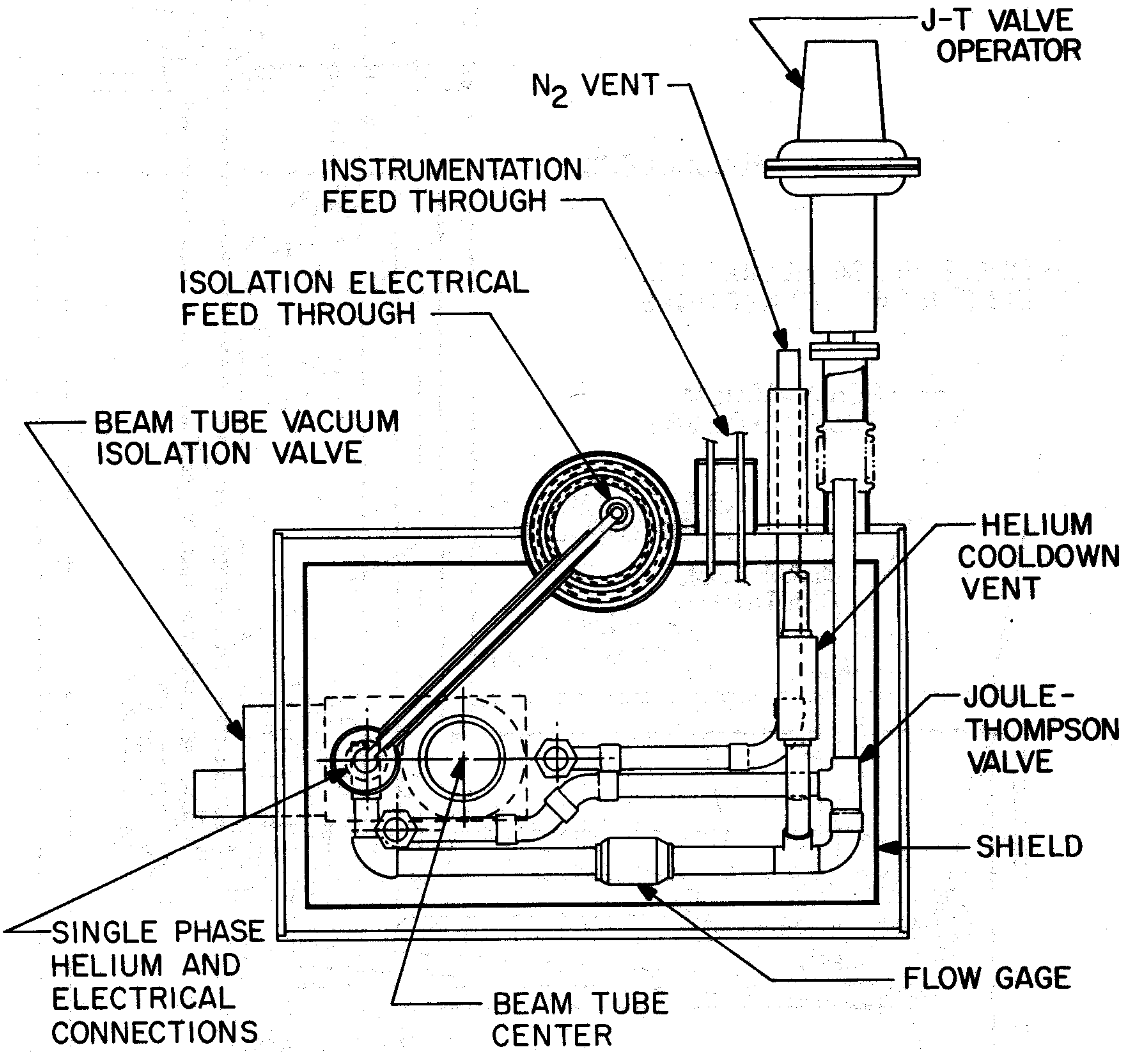


Fig. 4-9. Turnaround box.

The straight section bypasses occur at the long straight sections and at locations 17 and 48. At these locations a helium-transfer line containing the two power leads is brought out parallel to the beam tube for the length of the straight section. Straight-section space required for the bypass and cold-warm transitions is a total maximum of 25 in. for both ends. Isolation vacuum valves and sublimation pumps will require an additional 24 in. of straight-section space at each end. Figure 4-10 illustrates a typical bypass.

4.7 Cooldown and Warmup

If one attempted to cool down long strings of magnets in the normal operating mode, it would take several months or might be altogether impossible, because the magnets are heat exchangers and therefore most of the refrigeration that is supplied is heat exchanged with the return line and then vented. We therefore use single-pass cooling of the single-phase rather than loop flow, with the two-phase deadheaded. The wave front is very steep and travels through the magnet string much like a step function through a transmission line; the discharge remains at room temperature during almost the entire cooldown cycle.

Cooldown with the CHL operational is very straightforward. The satellite is tuned up in the liquefier mode, producing 126 ℓ/h, which is added to the 200 ℓ/h from the central (if one is cooling only one service building this might be as high as 2000 ℓ/h, stress, pressure drops, and thermo-acoustic oscillations permitting). This helium is run through the single phase of the magnets, returning to compressor suction by way of the cool-down lines, where it recompresses to 20 atm. The excess gas is then

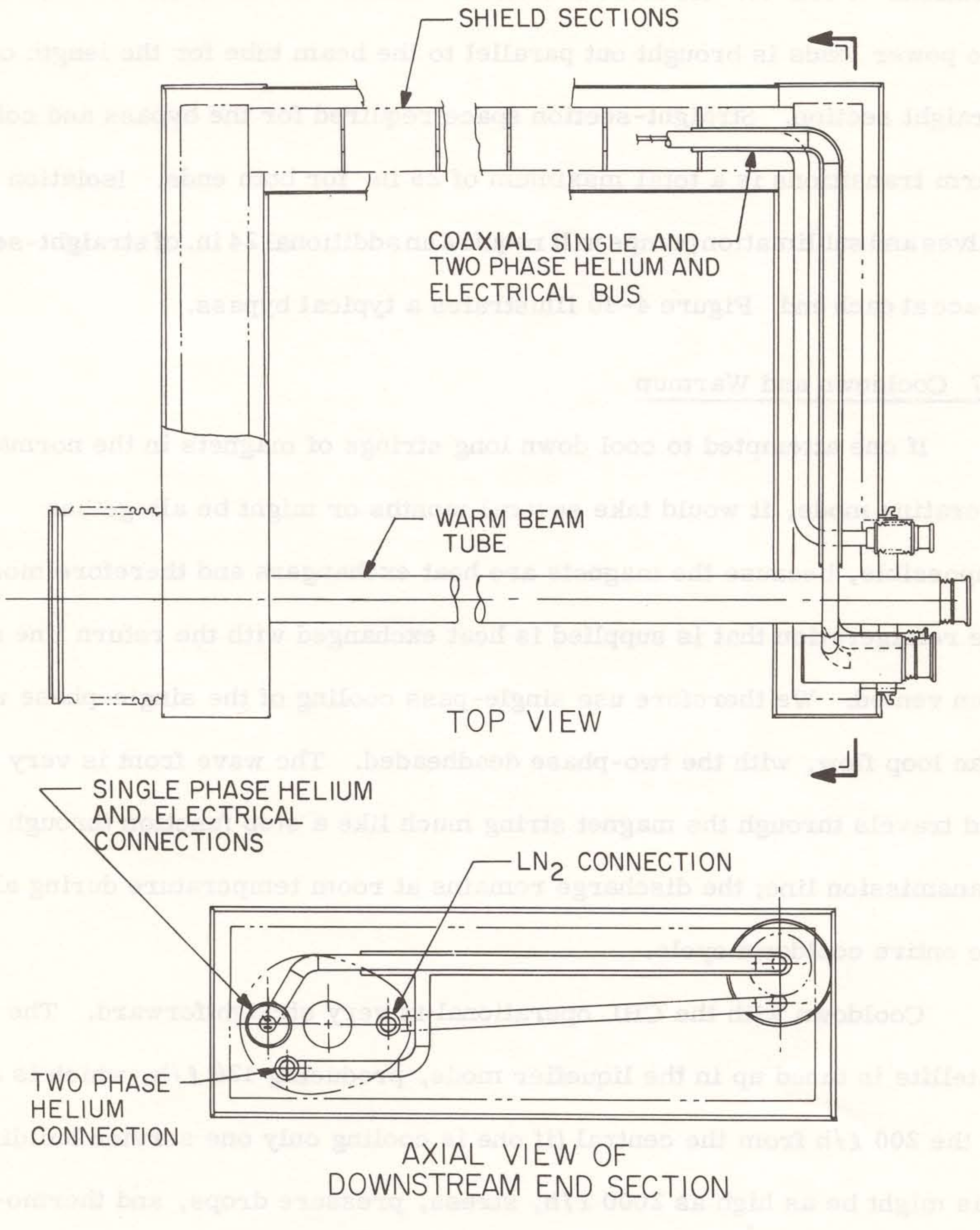


Fig. 4-10. Bypass.

returned to the discharge of the CHL compressor (13 atm), where it is reliquified. When the wavefront reaches one of the cool-down lines, it is shut off and the magnet JT is opened. When it reaches the second one, the same is repeated, 1000 ℓ are transferred from the central to fill the magnets, the dry engine is turned off and the satellite is tuned for the satellite mode.

If the CHL is not operational, cooldown is slightly more complicated, but can be carried out using the liquefier mode followed by the standby mode of the satellites. Since the CHL was not complete, this mode was used to cool the 25-magnet string in the A1 tests.

Cool down after a quench is a function of the energy dissipated in the magnet. For a quench during injection, recovery time should be less than 100 s. During the 25-magnet A1 test, the system recovered much faster than the length of time it took to turn on the power supply.

For fast recovery at high power levels we require a fast electronic valve control circuit which does the following:

(i) Fire relief or auxiliary cool-down valves at both ends of quenched half-cell in a time $\Delta t < 50$ ms.

(ii) Close JT valve in $\Delta t < 2$ s.

(iii) After 5 seconds, close valve on quad closer to refrigerator.

(iv) Run in cool-down mode, venting into suction header at the quad further from refrigerator until T_{out} equals 10 K.

(v) Close second quad valve and open JT valve.

(vi) Refrigerate and fill.

Warmup is a function of the electrical status of the magnets. If there is continuity in the electrical circuit, the string can be warmed up in 4 hours using either the main power supply or a special warmup supply.

If electrical continuity is lost, several heater supplies can be installed across the safety leads so that, combined with hot gas from the compressor, a heating rate of 50 kW can be achieved (10-20 h warmup).

If both electrical continuity is lost and there are large holes in the single-phase He cryostats, hot N_2 at 3 atm is connected and warmup takes several days.

4.8 Failure Modes

Because of the complexity of the system, it is highly probable that at any one time, one component may be down and several may be operating at reduced efficiency. The system must be designed to continue to cool the magnets with at most a reduced ramp rate. Table 4-IX gives projected replacement and beam-off times for various component failures. Times do not include an allowance for troubleshooting the system and travel time for the repair crew; troubleshooting in many cases can be longer than replacement times. The extremely rapid replacement time is possible because of our concept of separate cryostats and quick-disconnect vacuum U-tubes.

Table 4-IX. Operation in Failure Modes.

Defective Component	Consumption Replacement (ℓ/h) He	Consumption Replacement (ℓ/h) N_2	Times Beam Off (h)	Times Replacement (h)	Ramp Rate (min)	Action Taken	Comments
Normal operation	144	20	-	-	1		
Central Helium Liquefier	0	79	-	as needed	5	start gas engines	
Central Nitrogen Liquefier	144	20	-	as needed	1	buy N_2	\$105/h for total ring
Feed line	144	20	1.0	168-336	1	reverse flow	
Magnet	-	-	48	48	beam off		
Satellite Cold Box	-	-	48	48	beam off		
Satellite Compressor	144	20	-	as needed	1	turn on standby com-pressor	each comp. is 4% of total re-frigeration
Satellite Wet Expander	400	20	2×0.1	2	1	sat. JT valve	
Satellite U-Tube	as needed	20	0.1	0.1	beam off		
Feed U-Tube	as needed	-	0.5	0.5	beam off		