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Cryogenic Systems for the HEB Accelerator of the Superconducting Super Collider

Superconducting Super Collider Laboratory

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1.0 CRYOGENIC SYSTEM FOR THE HEB—GENERAL REQUIREMENTS

1.1 HEB Cryogenic System Geometry

The High Energy Booster (HEB) single ring, 10,800 m in circumference, is designed to be built in a tunnel located in a plane with an inclination of 0.2° parallel to the collider and is located 14 m above the plane of the collider. The highest point of the tunnel is close to H20 and the lowest point near H60. The difference in the elevations between these two points is approximately 16 m. Table 1 shows the depth of the HEB-tunnel and the surface elevation at the H10–H80 locations.

Table 1. Surface and Beam Altitudes for the HEB (m).

Location	Surface Altitude	Depth to Beamline	Beamline Altitude	Beamline Relative Altitude
H10	229.3	39.4	189.9	16.3
H20	247.4	57.7	189.7	16.1
H30	248.6	63.0	185.6	12.0
H40	233.6	55.0	178.6	5.0
H50	226.2	52.5	173.7	0.1
H60	226.6	53.0	173.6	0.0
H70	221.6	43.3	178.3	4.7
H80	215.0	30.2	184.8	11.2

The HEB is divided into eight “Beam Sectors,” as defined in the HEB Level 3B Specification.¹ This definition is used for beam physics and has no use for cryogenic design and operation.

For the cryogenic system design and operation, the HEB is divided into cryogenic sectors, strings, and sections, which are delineated by the eight major stations on the HEB lattice named: H10, H20, H30, H40, H50, H60, H70, and H80 (see Figure 1). These locations house the appropriate sector cryogenic feed equipment, cryogenic return equipment, and/or cryogenic isolation equipment. The HEB ring is served by two helium refrigeration plants located at the H20 and H60 sites. The supply of cryogens from the Surface Cryogenic Systems (SRS) to the Sector Tunnel Refrigeration Systems (SRT) is provided through vertical utility shafts near the refrigeration plants. Additional service shafts are located near the sector boundaries. The major power supply to the magnet rings and energy extraction systems is designed to use the same shafts and the same connection points to the magnet rings. A schematic of the HEB tunnel cross section is shown in Figure 2.

The HEB ring is divided into two cryogenic sectors, centered at H20 and H60. Sector H20 covers half of the HEB ring between H80–H10–H20–H30–H40. It has a helium refrigeration plant on the surface at H20. Sector H60 covers the other half of the HEB ring between H40–H50–H60–H70–H80. It has a helium refrigeration plant at H60. The boundaries of the cryogenic sectors at H40 and H80 are designed to enable flows of cryogens from one sector to the other and, if necessary, flows of nitrogen from the tunnel to the surface.

Each cryogenic sector is divided into two cryogenic strings, each with a cryogenic feed box at one end and a return box at the other end. The strings are segmented into sections connected to each other by U-tubes that enable the isolation of parts of the system for maintenance. A section is the smallest part of the ring that can be isolated, warmed up, and cooled down for maintenance. In the HEB a string contains two sections. The actual definition of the HEB sections is given in Table 2 and shown in Figure 1.

Figure 2. HEB Tunnel Cross Section.

Table 2. Definition of the Cryogenic Sector and Section Boundaries.

Sector H20 (north): H80-H20-H40		Sector H60 (south): H40-H60-H80	
Section H1	H80-H10	Section H5	H40-H50
Section H2	H10-H20	Section H6	H50-H60
Section H3	H20-H30	Section H7	H60-H70
Section H4	H30-H40	Section H8	H70-H80

There are six straight segments in the ring required for beam injection, beam extraction, beam abort, beam test, and other purposes. These segments contain those lengths of the beam tube that are warm. To bridge over the warm segments, the cryogens have to be transferred to Bypass Transfer Lines, which are specially designed cryostats. The straight segments are located in the vicinity of H10, H20, H40, H50, H60, and H80, each with a specific length and design as given by the HEB Level 3B specification.¹

Table 3 gives the lengths of the sections. The differences in the length of each section and the differences in their contents (*i.e.*, ring components) have to be carefully defined because of their impact on the parameters for normal operation (heat loads, pressure drops, *etc.*) and on the time duration for maintenance procedures. Table 4 gives the list of ring components in each section. Further details on the HEB specifications and requirements can be found in References 2-4.

Table 3. Lengths of the Sections in the HEB.

Section	Updated	Conceptual Design
H80-H10	1104 m	1480 m
H10-H20	1628 m	1480 m
H20-H30	1334 m	1220 m
H30-H40	1334 m	1220 m
H40-H50	1436 m	1480 m
H50-H60	1296 m	1480 m
H60-H70	1334 m	1220 m
H70-H80	1334 m	1220 m

The sections are further broken down into cells. The cell is the smallest repetitive group of magnets (dipoles and quadrupoles) in an accelerator with a specific function of beam optics. For cryogenic, vacuum, and mechanical purposes, the HEB cell is designed to confine insulating vacuum problems and magnet quenches to a cell, and to prevent the propagation of these problems to the adjacent cells. A regular HEB arc cell is 65 m long and contains four dipoles, two quadrupoles, and two spool pieces. The cell configurations are different at the end of arc sections and in the straight sections. Figure 3 shows the configurations for a regular arc cell, for a dispersion suppressor cell, and for cells with isolation equipment.

1.2 Cryogenic System Configuration

Figure 4 is a block diagram showing the major parts of the sector cryogenic system. The Sector Cryogenic System (SCS) is physically divided into two parts: the Sector Refrigerator Surface System and the Sector Refrigerator Tunnel System.

1.2.1 Sector Refrigerator Surface System (SRS)

The Sector Refrigerator Surface System (SRS) for the HEB has the same design, configuration, and capacity as the SRS for the Collider. Since the 4-K liquefaction, the 4-K refrigeration, and the 20-K heat loads of the HEB are different from the collider sector loads, the HEB refrigeration system has to be able to operate at a different working point.

The surface cryogenic system is described in detail in References 24, 33, and 34.

1.2.2 Sector Refrigerator Tunnel System (SRT)

The Sector Refrigerator Tunnel System (SRT) for the HEB is designed to serve one magnet ring (compared to the collider, which has two rings). This requires a special design of the tunnel distribution system to support the flow schemes for the normal operation modes and for the maintenance schemes.

The higher dynamic 4-K load of the HEB ring requires the vapor return line in the ring to be larger than in the collider (110 mm in the HEB, 86 mm in the collider). It also requires the 4-K liquid "return" line to be able to serve as a return line when the heat load is low (during standby mode) and as a feed line during normal operation (when the beam is on). These issues are discussed in more detail in Section 4.0.

The 20-K helium lines and the 80-K nitrogen lines and distribution boxes are designed such that the flow can be maintained in both directions from one refrigerator to the other, clockwise, or counterclockwise, depending on the specific conditions that may change with time.

Table 4. HEB Cryostat Count.

		I120 SECTOR NORTHWEST										I160 SECTOR SOUTHEAST											
		STRING 1 - CCW					STRING 2 - CW					STRING 1 - CCW					STRING 2 - CW						
		-I18-		-H1-				-I12-		-I13-				-I14-		-I15-		-I16-		-I17-			
		1104 m		1628 m				1334 m		1334 m				1436 m		1296 m		1334 m		1334 m			
		H 80		H 10		H 20		H 30		H 40		H 50		H 60		H 70		H					
		LENGTH (m)	S	ARC	S	S	ARC	S	S	ARC	ARC	S	S	ARC	S	S	ARC	S	S	ARC	ARC	S	TOTAL
MAGNETS																							
HDM B	13.171	3	56	1	7	56	3	5	60	60	5	3	56	4	4	56	3	5	60	60	5	512	
HQM F	2.483	2	14		3	14	1	2	15	15	1	2	14	1	2	14	1	2	15	15	1	134	
HQM D	2.483	1	14	1	3	14	2	2	15	15	3	1	14	2	2	14	2	2	15	15	3	140	
Q1	1.785				2									1	1							4	
Q2	2.056				2									1	1							4	
Q3	1.785				2									1	1							4	
Q4	1.785				2									2								4	
Q5	1.785				2									2								4	
QS1 HQM3	3.141							2			2							2			2	8	
QS2 HQM4	4.23							2			2							2			2	8	
QS3 HQM4	4.23							2			2							2			2	8	
Families of SPOOLS																							
I1-SPXA	3.675	1	14		1	14	1	3	15	15	2	1	14	4	3	14	1	3	15	15	3	139	
I1-SPRA	3.675	2	14		6	14	1	2	15	14	1	2	14	3	4	14	1	2	15	14	1	139	
I1-SPRI Short	3.675								0.5	0.5								0.5	0.5			2	
I1-SPRI	7.35			0.5	0.5									0.5	0.5							2	
I1-SPRF	7.35						0.5	0.5									0.5	0.5				2	
I1-SPRE	7.35	0.5									0.5	0.5									0.5	2	
SPXA-RB (SPXU)	3.675				9			2			2							2			2	17	
SPRA-EB (SPRB)	3.675				2			2			2			2				2			2	12	
SPRA-TB (SPRT)	3.675				9			2			2							2			2	17	
EMPTY CRYOSTATS																							
I1ECL	6.585	5		2	4		6	9			10	5		25	25		6	8			10	115	
I1ECS	2.8	1			7			1			1	1										11	
BYPASSES																							
BYPASS (m)					529			226			228			112				228			228	1551	
BPCR-13	13				33			15			15			8				15			15	101	
BPCR-S	6.5				11			3			3			1				3			3	24	
BPTB	2				9			2			2							2			2	17	
BPEB	2				2			2			2			2				2			2	12	

(a)

(b)

(c)

All dimensions are in meters

B = Regular Arc Dipole 13.171 m long

Q = Regular Arc Quadrupole

SPXA = Arc Spool without Recooler with Vacuum Barrier

SPRA = Arc Spool with a Recooler without Vacuum Barrier

EC = Empty Cryostat (standard module length designed for the HEB = 6.585 m)

The quadrupole located at the boundary between the D.S. cell and the straight segment may have a different length than a regular arc quadrupole. Therefore the adjacent EC may be different.

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Figure 3. HEB Cells.

Figure 4. Sector Refrigeration System Block Diagram. (See Table 5 for the index to numbers used here.)

1.2.3 Flow of Cryogenics

The cold components (cryostats with superconductive magnets, spool pieces, empty cryostats, bypass cryostat transfer lines, etc.) in the HEB ring are designed to be refrigerated by single-phase helium flow controlled at a temperature of 4 K to maintain the magnet windings in the superconductive state. To minimize the heat load on the 4-K loop, the magnet cryostats are designed to provide high-quality thermal insulation achieved by two thermal shields, at nominal temperatures of 20 K and 84 K, contained in a high vacuum chamber with multilayer insulation (MLI). There are six cryogen lines in a cryostat, plus a warm line external to the cryostat, as follows:

Line 1, single-phase feed. For normal operation, a nominal flow of 100 g/s at 4 K, 0.4 MPa helium through the magnets maintains the coils in the superconductive state. This flow enters a string at one end and exits at the other end while being recooled periodically along the string. The cross-sectional area for this flow is defined by the sum of the different cooling channel cross sections within the coldmass. A small amount of this feed stream is tapped off at different locations along the string for the refrigeration of the high-current leads, the bypass leads, and the current leads for the corrector magnets.

Line 2, single-phase return. This line, which has an ID of 45.2 mm, is mounted in the vacuum envelope alongside the magnet coldmass. It carries the single phase from the end of the string back to the refrigerator. A sizable portion of this return stream is injected into the recoolers. The heat load of the HEB strings is higher than that of the collider, and the high boil-off rate in the recoolers may require supply of additional single-phase flow from the other end of this line.

Line 3, 4-K helium vapor return. This line, sized at 110 mm ID for the HEB (compared to 86.5 mm ID for the collider), returns the boil-off helium from the recoolers to the cold compressor installed in the tunnel. The compressor discharges the vapor to the refrigerator, located more than 60 m above the tunnel. For normal operation the flow direction may be defined arbitrarily.

Line 4, 20-K helium. An 82.5-mm-ID pipe is used for the 20-K shield refrigeration loop. The design flowrate is 100 g/s at 0.3 MPa. The flow is routed from one refrigerator through the two connecting strings to the other refrigerator.

Line 5, 80-K LN₂ shield line. This 57.2-mm-ID line is used to distribute the liquid nitrogen in the tunnel for the refrigeration of the 80-K shield and to supply liquid nitrogen to the refrigeration plants for precooling.

Line 6, 80-K GN₂ shield line. A second 57.2-mm-ID line is used to return the nitrogen vapor produced in the nitrogen recoolers to the helium refrigerator for precooling purposes. The vapor is vented afterwards to atmosphere at 300 K or is used in the regeneration skids.

Line 7, warm return header. Sized at 213 mm ID, this header is installed in the tunnel and is used to return the warm helium flow from the current leads. It is also used to return warm helium during cleaning, cooldown, and maintenance processes. An alternate design calls for two 100-mm-ID warm headers, one used for cooldown and warmup flows, and the other for current lead return flows.

The insulating spaces around the cryogenic components (magnets, spool pieces, and transfer lines) are evacuated to 1.3×10^{-2} Pa by mechanical pumps and to 1.3×10^{-5} Pa by cryopumping. This vacuum is required to minimize the heat load on the coldmass. The insulating space is bounded radially by the outer walls of the cryostat and axially by the vacuum barriers located in the spool pieces. The insulating vacuum volume between two vacuum barriers (65 m apart) is approximately 19.5 m³.

Cross section of an HEB dipole cryostat is shown in Figure 5:

Table 5. Sector Station Cryogenic System State Points.^a

Loc	Description	Temperature (k)	Pressure (bar)
1	Single-phase helium feed	4.0	4.0
2	Single-phase helium return	4.0	3.5
3	Gaseous helium return	3.95	0.77
4	20-K shield feed	14–18	3.0
5	20-K shield return	28 max.	2.0
6	Gaseous nitrogen return	85	1.5
7	Liquid nitrogen flow	80–85	3.0–10.0
8	LHe supply from refrigerator	4.45	4.0
9	Cold compressor return to surface	6.1	1.4
10	Single-phase helium return to dewar	4.3	3.5
11	Warm helium gas return	305	1.1
12	Nitrogen gas	85	1.3
13	High-pressure helium	308	20 nominal
14	Medium pressure helium	303	3 nominal
15	Low-pressure helium	303	1.05
16	20-K return pressure helium	303	1.5 nominal

^aIndex to numbers in Figure 4.

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Figure 5. HEB Dipole Cross Section.

1.3 Normal Modes of Operation

The Normal Modes of Operation of the cryogenic system are required for the following:

1. Standby: when the machine is cold and ready for beam injection. The heat load is static load only.
2. When the machine is cold and the beam is on. The heat load is static plus dynamic.

These two modes are expected to be steady, and the discharge flows from the refrigerator are expected to be equal to the return flows from the tunnel.

The basic requirement of the cryogenic system is to maintain the temperature in the superconductive magnet rings below 4.3 K. The temperature control of the 4-K helium system is based on a repetitive recooling system. This in turn depends on the vapor pressure level in the vapor return line. Given that a recoler can be installed in the system every 65 m (or one every cell), and given the heat load of the various ring components (see Section 3.0), the following flows are required in order to maintain the required temperature range for normal operation.

1.3.1 4-K Flows

Sector H20: 4-K, 100-g/s, helium supplied from the surface to the cryogenic feed box (SPRF) at H20 runs through the two strings to the cryogenic return boxes (SPRE), located at H80 and at H40 (string 1 = H20 to H80, string 2 = H20 to H40).

Sector H60: 4-K, 100-g/s helium supplied to the cryogenic feed box (SPRF) at H60 runs through the two strings to the cryogenic return boxes (SPRE), located at H40 and at H80 (string 1 = H60 to H40, string 2 = H60 to H80).

For standby operation (when the beam is off), the 4-K liquid and vapor helium return flows are both brought back to the refrigerator for reprocessing.

During normal operation (when the beam is on), the high heat load of the HEB requires 4-K helium to be supplied to the system through both the feed line and the return line at the SPRF. All the 4-K helium supply through the 4-K feed and liquid return lines flows back to the refrigerator as 4-K vapor.

1.3.2 20-K Flows

20-K, 100-g/s helium for shield refrigeration is designed to run through the ring from the refrigerator at H20 to the refrigerator at H60 through the north arc; a second 100-g/s stream runs from the refrigerator at H60 to H20 through the south arc. The flow direction is chosen arbitrarily.

1.3.3 80-K Flows

80-K liquid nitrogen for shield refrigeration and for surface supply is designed to flow from H20 to H60 through both north and south arcs. The liquid nitrogen has to be periodically recooled using heat exchangers installed near the isolation spools outside the ring. (Other methods of nitrogen recooling are discussed in Section 2.0.) Vapor nitrogen generated in the nitrogen recooling system in the tunnel is brought back to the two surface refrigerators, warmed to 300 K, and vented to the atmosphere. The liquid nitrogen is imported to the SSC from external sources. The system is designed to operate with liquid nitrogen supplied from an external source, delivered at one location (772 g/s at H20) or at two locations (386 g/s at H20 and 386 g/s at H60). An alternative solution for normal operation calls for a large LN₂ delivery station in the collider and a LN₂ transfer line from the collider to the HEB.

The flow scheme for normal operation is shown in Figure 6. Figure 7 shows the location of the HEB relative to the collider and the connecting transfer line.

Figure 6. Normal Operating Flows.

Figure 7. HEB-to-Collider Connection.

1.4 Safety

System safety and safe operation of the machine are major requirements. (See SCDR⁴ and HEB Level 3B Specification.¹) Safety issues relating to cryogenics include the following:

1. System response in case of a quench. The cryogenic system has to remove and recover the warmed helium in a way that the pressure in the system remains below certain limits. Detailed analyses of the quench processes are given in References 10–12.
2. System response in case of a line rupture. The cryogenic system has to minimize the flow of cryogens into the cryostat-insulating vacuum chamber and eventually into the tunnel, and maximize the return flow to the surface. Analyses of line ruptures are given in References 7–9 and 19.
3. System design. The cryogenic system has to be designed to have the minimum possible inventory of cryogens and to operate at the lowest possible pressure. This is to minimize the amount of cryogens vented into the tunnel in case of emergency or line rupture, and to minimize the time response of the system.
4. Cooldown process from 300 K to 4 K and warm-up back to 300 K are to be performed in the shortest time possible without causing excessive thermal stresses in the system. This time is limited by the allowable gradient of the thermal wave and by the high pressure limit during warm-up or cooldown. Cooldown and warm-up processes are discussed in detail in References 82 and 86.

1.5 Maintenance—General Requirements

There are two types of maintenance processes required: When maintenance is performed while the system is cold (for example, when vacuum is degraded and the activation of vacuum pumps may do the correction); and when a ring component has to be replaced. This requires section warm-up and cooldown.

The various cryogenic processes for maintenance purposes are:

- Sector cooldown from 300 K to 4 K
- Sector warm-up from 4 K to 300 K
- Section warm-up for repair
- Section cooldown after repair
- Sector warm-up to 20 K for gas desorption
- System warm-up to 80 K for long-term storage.

The basic system requirement is to perform all the maintenance processes in the shortest possible time. (The various time budgets related to the processes are given in References 83 and 84.) The time for all these cryogenic processes depends on the following:

- Refrigerator capacity. During the cooldown and warm-up cycles, large quantities of helium and nitrogen vapor are generated in the rings. These have to be brought back to the surface; the helium has to be reliquefied in the refrigerator, and the nitrogen has to be warmed to 300 K before being vented to the atmosphere. This places additional demand on the refrigerator, on top of the supply of the cryogens for cooldown and warm-up.
- Pressure. A decrease in the process time may be achieved by increasing the flow of cryogens. This requires raising the supply pressure. However, the pressure level is limited, particularly when temperature changes are involved.
- The allowable longitudinal temperature gradient in the magnet strings limits the cryogen flow rates and the supply pressures.

The detailed scenario for the maintenance cycle for the HEB is discussed in Section 5.0.

1.6 Nitrogen System for the HEB

A block diagram showing all functionalities of the SSC nitrogen system that serves both the collider and the HEB is given in Figure 8. Liquid nitrogen for the SSC is designed to be generated outside the SSC sites, imported by trucks or through pipes, and delivered to the system at one or more supply points. The HEB nitrogen supply should be independent of the collider and is designed to operate with its own supply of nitrogen. This requires special nitrogen delivery stations at one —or both— of the H20 and H60 locations.

The HEB is also designed to have a collider-to-HEB transfer line through which nitrogen may be supplied from the collider to the HEB. This seems to be a more effective way to run the machine during normal operation. In any case, each refrigeration system (at H20 and at H60) must be equipped with large nitrogen dewars and delivery stations to be used during the cooldown process and when the collider-to-HEB transfer cannot be operated.

The total demand of liquid nitrogen for normal operation of the HEB is 772 g/s: 332 g/s for the tunnel and 220 g/s for each surface refrigeration system. Figure 9 shows a comparison of the three methods of LN₂ supply to the HEB. These three methods are discussed in References 44–46.

Figure 8. SSC Nitrogen System Functionalities.

LOAD: TOTAL 84 K FLOW = 772 g/s LN₂ = 2779 kg/h = 67 ton/day

1) LOCAL GENERATION

Ideal work 768 kJ/kg*0.772 kg/s
assuming 30% Carnot efficiency
= 1.9 MW=2550 HP

2) LOCAL STORAGE

SRS dewar = 75000 liters
~ max 54000 kg (one day supply /dewar)

3) TRANSPORTATION

22.5 tons/truck => required three trucks/day
If there is no supply for one day and the refill is required in 6 hours,
parking for 3 trucks is needed.

F - SPRF
E - SPRE
I - SPRI

Figure 9. Alternative LN₂ Supply Systems for the HEB.

2.0 CRYOGENIC SYSTEM COMPONENTS

2.1 Subsystems and Assemblies

2.1.1 Cryogenic System Block Diagram

A general block diagram of the cryogenic system for the HEB sector is given in Figure 4. The Sector Cryogenic System (SCS) organization block diagram is shown in Figure 10. The status of the cryogenic system and equipment design is given in Reference 27.

2.1.2 HEB Refrigerator and Surface Distribution System Design

The Sector Refrigeration Surface System (SRS) is designed to handle a variety of operating conditions. Its primary function is to provide refrigeration to the magnet strings. It also provides services such as cleanup, cooldown, warm-up, and maintenance to the magnet strings. In order to meet the operating requirements for each mode, a minimum set of components is needed to enable the reconfiguration of the system by including or excluding specific subsystems, and to adjust the capacity and the throughput of each subsystem. Thus the design must also provide the appropriate overall control philosophy of the system, in particular that of the liquid management scheme. The liquid management system, which serves as the interface between the surface system and the tunnel cryogenics, should be capable of handling the various operating conditions of the system.

Special effort was invested in the definition of the system configuration, including:

- Independent system for each load
- Integration of the 4-K and the 20-K loads
- Two identical systems (two parallel plants or two parallel cold boxes)
- One larger system per sector.

The larger serial system containing one cold box was finally chosen. (The other systems were excluded because of much higher cost.)

To define the detailed configuration, a series of process modeling and simulation studies were performed. These included the comparison between various choices, such as

- Warm compression of the return helium gas vs. cold compression
- Cold compressor placement (in the tunnel or on the surface)
- Number of expanders.

The compressor and coldbox sizing were done to optimize the power requirements, the number of skids, and the heat exchanger sizing, which resulted in a system that can be built with existing or available equipment and has capacity adjustment and turndown capabilities.

The resulting basic configuration design is shown in Figure 11. The sector refrigerator surface system flow diagram is shown in Figure 12. The corresponding thermodynamic T-s diagram is presented in Figure 13. (The thermodynamic analysis for the HEB is incomplete. The diagrams in Figure 13 are taken from Reference 43 and are offered as illustrative examples.)

Sector Surface Refrigeration System consists of two major sub-systems: the Compressor and Gas Management System (CMS) and the Refrigeration System (RFS).

Figure 10. Hierarchical Organization Block Diagram of the SRS.

Figure 12. Sector Refrigerator Surface System Flow Diagram.

100% Refrigeration

50% Refrigeration
+
50% Liquefaction

100% Liquefaction

Figure 13. T-s Diagram for the SRS.

The Compressor System and Gas Management System (Figure 14) consists of:

1. Compressor Group. Two-stage compression of helium gas for the refrigerator. The available power for operation at design load is 5 MW.
2. Oil Removal System. Fine oil removal system to remove oil from the compressor discharge helium flow.
3. Gas Management System. A set of control valves that manages the overall inventory in and out of the system at the warm end of the refrigerator and allows the refrigerator to follow load changes.
4. Gas Storage. Warm gas storage capacity of 300 000 gal up to 19 bar.
5. Auxiliary Equipment 1. Bearing gas compressor skid, oil management system for compressor system, utility stations, instrument air system.
6. Piping Network 1. Warm piping network between gas storage, compressor system, and coldbox.

The Refrigeration System (Figure 15) contains:

1. Coldbox System. Configured in a series arrangement: The first coldbox (CBW) contains dual, full-size heat exchanger cores, the nitrogen boiler, and 80-K adsorber beds. The second coldbox (CBC) contains the expanders, the low-temperature heat exchangers, 20-K beds, and buffer volume.
2. Liquid Management System. A special surface distribution box serves as the precooler, interface, and distribution manager between the coldboxes, the LHe storage system, and the tunnel cryogenic system. Accommodations have been made for future installation of a LHe circulation pump into the system.
3. Liquid Helium Storage System. Two 30 000-gal dewars provide liquid storage capacity to hold the entire liquid inventory of the magnets in one cryogenic sector.
4. Nitrogen Dewar and Gas Generation System. Provides liquid nitrogen for precooling in the refrigeration system and warm gas generation for adsorber bed regeneration usage. The dewar capacity is sized for 2 days of normal sector usage.
5. Auxiliary Equipment 2. Consists of oil brake skids if oil-bearing expanders are used, regeneration skids to regenerate adsorber beds in the coldbox, dehydration regeneration skid to regenerate dehydration beds, dehydration unit for moisture removal from the helium loop, additional utility stations, utility vacuum system, and an additional instrument air receiver tank.
6. Piping Network 2. Warm and cold piping system interconnecting the coldbox, the surface distribution box, the dewars, the regeneration skids, and dehydration skid.

The physical layout of the surface equipment for the HEB H20 and H60 sites is shown in Figure 16. Further details can be found in Reference 2.

Figure 14. Compressor and Gas Management System (CMS) Interfaces.

Figure 15. Refrigerator System (RFS).

Figure 16. SRS Layout, HEB H20 and H60 Sites.

2.1.3 HEB Sector Refrigerator Tunnel System Configuration

The boundaries of the SRT are at the outlet of the surface distribution system and include the shaft transfer line, the cold compressor installed in the tunnel, the tunnel horizontal transfer line, the tunnel distribution box, the nitrogen distribution box, the nitrogen recooling system, the magnet ring components, and the auxiliary end box installed at the boundary between two sectors, which is needed to control the flow of cryogenics from one sector to the other and the return flows to the refrigerator. Process flow diagrams for the SRT components were developed to cover all the requirements, and certain mechanical conceptual designs were developed to define the space, interfaces, and installation requirements. Figure 17 shows an isometric view of the feed assembly in the SRT. Figure 18 is a flow diagram for the feed assembly. Figure 19 shows the flow diagram for the auxiliary end box.

In several locations along the rings, warm equipment is designed to be in series with the superconducting magnets. Cryogenics are designed to flow around these warm sections using cryogenic bypass transfer lines (CBTL). These transfer lines contain cryogenic pipes and superconducting buses that must be maintained at the 4-K level. The CBTL, together with the connecting boxes to the cold magnets, the special boxes with recoolers and vacuum barriers, and the cryogenic and vacuum instrumentation, are all part of the SRT.

Also included in the SRT are nitrogen subcoolers designed to be installed and connected to isolation spools at the end of each cryogenic section. These subcoolers are heat exchangers that periodically recool the shield liquid nitrogen flow.

2.1.4 Nitrogen Distribution and Recooling Systems for the HEB

The design temperature of the 80-K shield is based on an average of 84 K. The shield design, the flow rates of the nitrogen in the cryostats, the recooling schemes, and the actual heat loads are the factors that affect the average temperature. The minimum achievable temperature of LN in the tunnel is 80 K, compared with 78 K suggested in the CDR. This results from the minimum achievable pressure in the vapor return line which is 0.14 MPa.

If the thermal conductance between the LN line and the shield is reasonably good, *i.e.*, the pipe is welded to the shield, then for a nominal load of 3.2 W/m, the average shield temperature is expected to be around 90 K, which is higher than suggested in the CDR. This will cause an increase in the heat radiated from the 80-K shield to the 20-K shield.

To limit the temperature rise in the 80-K system, the following solutions were suggested and analyzed:

1. Use of compact recoolers in all the feed, isolation, and end spools, *i.e.*, at every cryogenic section. The LN flow circulation is maintained as high as necessary to keep the temperature in range. The vapor line returns the vapor from the recoolers to the refrigerator.
2. Use the liquid line (line 5) for liquid flow distribution. The vapor line is used for controlled continuous recooling. For this solution, special phase separators/recoolers and circulation pumps are needed at H20 and H60. A compact recooler is needed in each of the other isolation spools and end spools.
3. The liquid line is connected to the vapor line in the End Spool (SPRE) so that the vapor line may be flooded. The pressure of the vapor line in the SPRF is maintained as low as possible (0.14 MPa). No additional compact recoolers are required in the system.

Analysis of the different methods is given in References 44–46 and 49–51. The LN flow around the HEB ring for normal operation, including one delivery station at H20 and compact recoolers (see option 1 above), is shown in Figure 20. The GN flow directions are also indicated on the figure.

Figure 17. Isometric View of the Feed Assembly for the HEB.

Figure 18. Flow Diagram for the HEB Feed Assembly.

Figure 19. Flow Diagram for the HEB Auxiliary End Box.

2.2 Tunnel Cryogenic System Components

2.2.1 HEB-to-Collider Transfer Line

This transfer line is not mentioned in any earlier documents such as the CDR or the SCDR. It results from the requirements to minimize operating costs and to enable flexibility in the LN supply and sharing of helium loads between the collider and the HEB. It was suggested that the functionality and design of this line will be based on the cost comparison between reduction of the operating costs of the HEB with the installation cost of this line, which requires an additional 14-m shaft. The location of this line was defined between the cryogenic bypass transfer line in the collider and the bypass transfer in the HEB in the West Complex.

The minimum design of this line calls for a single vacuum-jacketed tube, 50 mm in diameter, used only to transfer liquid nitrogen from the collider to the HEB. The maximum design calls for a vacuum-jacketed transfer line with 7 lines and valve box, as shown in Figure 21.

The HEB-to-collider transfer line starts with a special box in the HEB bypass near H10, and ends at a special box in the Collider West Straight bypass transfer line. The transfer line is routed through a special shaft designed with radiation shields. The vertical distance between the collider and the HEB is 14 m; hence the minimum length of the line is 25 m. An individual vacuum system is designed for this transfer line.

2.2.2 Shaft Transfer Line (Vertical Transfer Line)

The shaft transfer line (STL) is the conduit for cryogen flow between SRS and the tunnel equipment. STL has seven lines: 4-K He supply, 4-K He return, GHe return, 20-K He supply, 20-K He return, 84-K LN, and 84-K GN, all enclosed in a common vacuum jacket. The shaft transfer line system requirements are given in Table 6.

Table 6. Shaft Transfer Line System Requirements for the HEB.

Cryogen Flows	P		T	Flow Rate	
	Design (bar)	Nom (bar)	(K)	Design (g/s)	Nom (g/s)
4-K He Supply	20	4	4.5	400	200
4-K He Return	20	3.5	4.3	300	250
4-K GHe Return	10	1.1	4	450	450
20-K He Feed	20	3	16.5	200	100
20-K He Return	20	2	24	200	100
80-K LN ₂	20	10	84	750	750
80-K GN ₂	20	1.5	84	400	250

The HEB has two shaft transfer lines, to be installed in the utility shafts at the midpoint of the sectors. The total length of each STL depends on the depth of the individual utility shaft as well as on the respective locations of the surface distribution box and the cold compressor box in the tunnel. The STL is designed to hang vertically on the wall of the utility shaft and has a vacuum pumpout port on each end. The shaft depths can be found in Table 1.

The vacuum jacket can be made of 600-mm carbon steel pipe, designed to maintain a vacuum of $1.5\text{E-}5$ Pa with a maximum leak rate $10\text{E-}6$ std-cc/s. An 80-K thermal shield (gage 19 copper sheet soldered to the 80-K lines) and multilayer insulation should be used to reduce heat leaks into the line (two 32-layer MLI blankets over the thermal shield and a 16-layer blanket over each cryogenic line). The estimated heat load for the STL is 0.4 W/m for the 4-K lines, 0.4 W/m for the 20-K lines, and 3.0 W/m for the 84-K lines. The STL will be built in standard, 12-m-long, straight modules, with standard and special elbow pieces and special makeup pieces, and will be assembled on site. The estimated weight of a module is 150 kg/m.

Figure 22 shows design details of the shaft transfer line.

Figure 21. HEB-to-Collider Transfer Line.

Figure 22. STL Geometry and Piping Details.

2.2.3 Cold Compressor Box and Cold Compressor

Each sector requires a cold compressor module to be installed in the tunnel near the utility shaft. A cold compressor module (Figure 23), consisting of a cold compressor and a separate cold compressor box, provides the low pressure level in the vapor return line, which is the main temperature controlling factor. Two modules are needed for the HEB: one each at H20 and at H60.

The cold compressor must follow the various operating modes—design, nominal, and standby—as determined by magnet system demand, and by refrigerator capacity and availability. Table 7 shows the design conditions for each mode, with the minimum required isentropic efficiencies for the cold compressor. The compressor shall be capable of safe start and shall continue to operate through a wide range of inlet and outlet temperatures, pressures, and flow rates. It is also necessary to be able to bring the compressor on line from room temperature with the rest of the system at operating conditions. The system shall be designed with either a water- or air-cooling system, and high-pressure helium gas will not be available for static gas bearing.

Modeling and simulation results for the cold compressor are detailed in References 80 and 81.

Table 7. Design Conditions for the Cold Compressor.

Mode of Operation	Inlet P (bar)	T (K)	Outlet P (bar)	Minimum Efficiency %	Flow g/s
Design	0.75	4.3	1.45	65	330
Nominal	0.75	4.3	1.40	60	264
Standby	0.75	4.3	1.35	55	138

Two separate boxes are designed to contain the cold compressor module: one for the cold compressor (two stages), and one for the cold compressor box, which includes control valves, a heat exchanger, a phase separator, strainers, and tubing. Both boxes are designed to have an 80-K shield and MLI blankets, and both are vacuum-insulated.

2.2.4 Horizontal Transfer Line (HTL)

The horizontal transfer line (HTL), connecting the cold compressor box and the tunnel distribution box, differs from the shaft transfer line (STL) only in its supports and installation. Whereas the STL is designed to be supported vertically in the shaft, the HTL will be supported horizontally from the tunnel ceiling. The HTL for each sector is approximately 23m long, with a vacuum barrier and a vacuum pumpout port at each end. The HTL is designed to have three standard length modules (6.0 m each): one module with a special length, and two end units with elbows, pumpout ports for the insulating vacuum, and relief valves. Each module has internal and external supports and uniform interconnect with bellows connections. Two units are required for the HEB.

2.2.5 Tunnel Distribution Box (TDB)

The tunnel distribution box is a nitrogen-shielded coldbox to be installed in a niche behind the feed spool, in the outer part of the ring (see Figures 17 and 24). It is vacuum-jacketed ($10E-5$ Pa) and connected to the cold compressor box through the horizontal transfer line. The TDB for the HEB has two short, vacuum-jacketed transfer lines, each containing six pipes, that feed cryogenics to the two magnet strings through the feed spool piece. (The collider-TDB feeds four strings.) The required valving and the flow diagram for the TDB-HEB are given in Figure 18.

Figure 23. Cold Compressor Box (CCB).

Figure 24. Tunnel Distribution Box (TDB).

2.2.6 Nitrogen Distribution/Pump Box (NPB) and Nitrogen Dump Tanks (NDT)

2.2.6.1 Nitrogen Distribution/Pump Box

Approximately 5 kg/s of liquid nitrogen is required for normal operation of the collider and the HEB. The liquid nitrogen will be imported by the SSCL and delivered to one or more locations. From the delivery points it will be distributed around the rings for ring refrigeration and to the 12 helium refrigeration plants for helium precooling. The distribution of the nitrogen in the tunnel is done through the nitrogen pipes in the magnet strings. The flow is controlled by the nitrogen pump boxes (NPB), which are installed in the tunnel near the tunnel distribution boxes.

The NPB will contain a nitrogen subcooler, two or more pumps, and associated valves. One pump is used for circulation of the main flows and for distribution of the nitrogen in the tunnel. A second pump is required for pumping liquid nitrogen to the surface dewar. The pumps will be configured for parallel operation and for interchangeable application (see Figure 20).

The subcooler in the nitrogen pump box will be designed to support flow rates up to 2 kg/s in each of two streams, with heat loads up to 6 kW per stream. The box will be an independent vacuum unit ($10\text{E-}5$ Pa) and will have ports for pumping and monitoring instrumentation. Figure 25 shows the conceptual design and the flow diagram for the nitrogen pump box.

2.2.6.2 Nitrogen Dump Tanks (NDT)

For the HEB, an uninsulated nitrogen dump tank (Figure 26) is to be installed in the tunnel niches near each of the feed and end spools. These tanks will be used for emergency venting and may be used during cooldown and warm-up. Each tank has a minimum capacity of 10 000 l. The liquid nitrogen dumped into these tanks will vaporize, and the vapor will be vented to the atmosphere through a pipe routed to the surface, as shown in Figures 18 and 19.

2.2.7 Nitrogen Compact Subcooler Box (NSB) and Continuous Recooling

To limit temperature changes in the 84-K shield, the liquid nitrogen must be re-cooled periodically. The expected heat load of the 84-K system is around 3.2 W/m per string, and the maximum temperature of the liquid nitrogen should not exceed 89 K. In order to cover the whole range of LN_2 flows, including the lowest expected flow rates, the subcoolers will be located: (1) in the nitrogen distribution box in the feed assembly, (2) in the auxiliary end box, and (3) near the isolation spools. The isolation spools (SPRI) are located approximately 1300m apart in the HEB; each SPRI has two cryostats connected to one another by six U-tubes. Thus it is reasonable to connect the LN_2 subcoolers through these U-tubes at the isolation spool locations at H10, H30, H50, and H70.

Figure 27(a) is a flow diagram for the nitrogen subcoolers. Figure 27(b) shows the flow diagram for continuous recooling. The continuous recooling scheme is detailed in Reference 46.

2.2.8 Auxiliary End Box (AEB)

The auxiliary end box contains a set of valves that connect the six cryogenic lines of the two cryogenic sectors in the HEB. The valves are required to transfer nitrogen flows across the sector boundaries during normal operation and to transfer helium flows during the "assist" mode. The auxiliary end box may be designed as a separate box or may be incorporated in the nitrogen subcoolers. It will be connected to the middle of the end spool, as shown in Figure 19.

2.2.9 Warm Vapor Return Header

A warm return header, sized at 213 mm ID, is installed in the tunnel. The warm header is used to return the warm helium flow from the current leads and to return warm helium during cleaning, cooldown, and maintenance processes. The warm header can also be used as a dump to relieve pressure in the ring (Line 1) under emergency conditions. An alternate design calls for two 100-mm-ID warm headers, one used for cooldown and warm-up flows, and the other for current lead return flows.

Figure 25. Nitrogen Pump Box (NPB).

Figure 26. Nitrogen Dump Tank.

a) Recoolers Near the Isolation Boxes

b) Continuous Recooling by Controlled Injection
of Liquid into the Vapor Line

Figure 27. Nitrogen Subcooling System: (a) Recoolers Near the Isolation Boxes; (b) Continuous Recooling
by Controlled Injection of Liquid into the Vapor Line.

2.3 Ring Equipment

2.3.1 Cryostat and Interconnect

The cold components in the HEB ring are housed in leak-tight cryostats designed to maintain an insulating vacuum and to provide high-quality thermal insulation through thermal shields and multilayer insulation (MLI).

The ring components interface with each other through interconnects. Two families of interconnects are required to enable the installation of the ring components:

1. the standard in-line axial interconnects for magnet-magnet, magnet-spool, or magnet-empty cryostat connections, and
2. off-line connections, including connections to the SPRF, connections between the SPRE and the auxiliary end box, U-tube connections between the two halves of the SPRI, and connections to the bypass transfer lines.

The interconnect requirements are documented in Reference 6.

2.3.2 Arc Spools SPXA and SPRA

Spools are cryogenic boxes that contain correction elements, cryogenic piping and valves, instrumentation, and electrical and vacuum system components. The cryogenic piping requirements for standard spools are the same as those for the superconducting magnets, as discussed in Section 1.2.

SPXA is a standard spool piece with a vacuum barrier to provide insulating vacuum on a cell basis (see Figure 3). SPRA is a standard spool piece with a recooling, but it does not have a vacuum barrier—as does its counterpart in the collider—due to the shorter length of a cell in the HEB. SPXA and SPRA both have a quench valve connecting Lines 1 and 4; they provide cooling for the bypass leads and corrector element power leads (CEPL). SPXA contains a single-phase relief valve venting to the tunnel, and SPRA has a cooldown valve connecting Line 1 to the warm header. Figure 28 is a schematic for the cryogenic equipment and instrumentation in SPXA and SPRA. SPXA and SPRA for the HEB have a slot length of 3.675 m compared to 5.85 m in the collider. Figure 29 shows a conceptual design of the SPXA/SPRA.

2.3.3 SPRF

SPRF are spool pieces located at H20 and H60 that connect the corresponding tunnel distribution box to the HEB ring. SPRF has a recooling, a quench relief valve, cooldown and relief valves for each of the six lines, pressure and temperature instrumentation on each of the six lines, power leads, CEPL, and a beam tube transition joint for each of the two strings connected to it on either side. Figure 30 shows a schematic for the cryogenic equipment and instrumentation in SPRF. SPRF for the HEB has a slot length of 7.35 m and is very similar in design to the SPRF for the collider. Figure 31 shows a conceptual design for the SPRF.

2.3.4 SPRI

SPRI are spool pieces located at H10, H30, H50, and H70 that allow isolation of cryogenic sections for maintenance (warm-up and cooldown). The cryogenic connections between the two halves of the SPRI are made through U-tubes, together with a nitrogen subcooler box for the nitrogen system. The SPRI at H10 and H50 have slot lengths of 7.35 m and are similar in design to the SPRF. The SPRI at H30 and H70 have slot lengths of only 3.675 m and require a special design. Figure 32 shows a schematic for the cryogenic equipment and instrumentation in SPRI. Figure 33 shows a conceptual design for the 3.675-m-long SPRI.

Figure 28. Cryogenic Equipment and Instrumentation for SPXA and SPRA.

Figure 29. Conceptual Design of the SPXA and SPRA.

	DO	DI	AO	AI	SCDR	
QUENCH VALVE ACTUATOR	2				✓	
QUENCH VALVE POSITION		4			✓	
QUENCH VALVE TEMPERATURE				2	✓	
COOLDOWN VALVE ACTUATOR	2				✓	
COOLDOWN VALVE POSITION		4			✓	
COOLDOWN VALVE TEMPERATURE				2		
RECOOLER VALVE ACTUATOR (COUNTED AS PART OF THE SPRF)			2		(✓)	
RECOOLER VALVE POSITION (COUNTED AS PART OF THE SPRF)				2	(✓)	
RECOOLER LIQUID LEVEL (COUNTED AS PART OF THE SPRF)				2	(✓)	
RECOOLER INLET TEMPERATURE (COUNTED AS PART OF THE SPRF)				2	(✓)	
RECOOLER OUTLET TEMPERATURE (COUNTED AS PART OF THE SPRF)				2	(✓)	
SINGLE PHASE RELIEF VALVE TEMPERATURE				2	✓	
SINGLE PHASE RETURN RELIEF VALVE TEMPERATURE				2	✓	
GH ₆ RETURN RELIEF VALVE TEMPERATURE				2	✓	
20 K H ₂ RELIEF VALVE TEMPERATURE				2	✓	
LN ₂ RELIEF VALVE TEMPERATURE				2	✓	
GN ₂ RELIEF VALVE TEMPERATURE				2		
SINGLE PHASE PRESSURE				2	✓	
SINGLE PHASE RETURN PRESSURE				2	✓	
GH ₆ RETURN PRESSURE				2	✓	
20 K H ₂ PRESSURE				2	✓	
LN ₂ PRESSURE				2	✓	
GN ₂ PRESSURE				2		
CEPL COOLING VALVE ACTUATOR	1					
CEPL COOLING VALVE POSITION		1				
POWER LEADS CONTROL VALVE ACTUATOR			4			
POWER LEADS CONTROL VALVE POSITION				4		
POWER LEADS TEMPERATURE				4		
COOLDOWN VALVE ACTUATOR LINES 2, 3, 4, 5, 6	10				✓ (5)	
COOLDOWN VALVE POSITION LINES 2, 3, 4, 5, 6		20			✓ (5)	
COOLDOWN TEMPERATURE LINES 2, 3, 4, 5, 6				10		

Figure 30. Cryogenic Equipment and Instrumentation for SPRF.

Figure 31. Conceptual Design of the SPRF.

Figure 32. Cryogenic Equipment and Instrumentation for SPRI.

Figure 33. Conceptual Design of the SPRI at H30 and H70 (3.675 m long).

2.3.5 SPRE

SPRE are spool pieces located at H40 and H80 that allow for sector-to-sector connections through the auxiliary end box. SPRF has a quench relief valve, cooldown and relief valves for each of the six lines, pressure and temperature instrumentation on each of the six lines, power leads, CEPL, and a beam tube transition joint for each of the two strings connected to it on either side, but it has only one recoolers. Figure 34 shows a schematic for the cryogenic equipment and instrumentation in SPRE. SPRE for the HEB has a slot length of 7.35 m and is very similar in design to the SPRF.

2.3.6 Special Spools

2.3.6.1 SPR4, SPR1, SPX1

SPR4, SPR1, and SPX1 are special spools in the HEB straight segments. These spools are similar in design to the SPRA and SPXA, but have different slot lengths.

2.3.6.2 SPRB, SPRT, SPXU

SPRB and SPRT are special spools that connect the HEB ring components to the cryogenic bypass transfer lines used in the straight segments. SPRB and SPRT are basically an SPRA with a short extension for the connections to the bypass. SPRB connects a long string of magnets to one end of a cryogenic bypass. The connections contain the six full-size cryogenic lines and the superconducting bus. A schematic of SPRB is shown in Figure 35. SPRT connects isolated cryostats to the cryogenic bypass. The connections contain the full set of six cryogenic lines and the superconducting bus, but the 4-K vapor return line and the 20-K line may be less than full-size.

SPXU are special spools attached to an isolated cryostat used to turn around cryogens. SPRB, SPRT, and SPXU have warm-to-cold transitions and a warm beam tube valve. A schematic of an isolated cryostat including an SPRT and SPXU is given in Figure 36.

2.3.7 Empty Cryostats (EC)

There are cold drift segments in the dispersion suppressors, as defined in the half-cell diagram (Figure 3). There are also cold drifts in the straight sections. These drifts will be empty cryostats that contain the cold tubes for the 4-K, 20-K, and 80-K lines as well as the cold beam tube. The longer drifts are broken into a minimum number of viable lengths of empty cryostats. A standard empty cryostat module has a slot length of 6.585 m. There are also several other empty cryostats with shorter slot lengths. The empty cryostats are designed to have the same interconnect as the magnet-to-magnet and magnet-to-spool interconnects. Special design is needed to shield the magnetic field generated around the cold bus and to prevent interaction with the beam. To enable this, the cold bus is located at a distance from the cold beam tube. The standard empty cryostat module has also an expansion vessel in which the cold bus expansion loop can be accommodated. A cross section of the proposed empty cryostat design is given in Figure 37(a) (see Reference 57), and a flow scheme is shown in Figure 37(b).

	DQ	DI	AO	AI	SCDR		
QUENCH VALVE ACTUATOR	1				✓		
QUENCH VALVE POSITION		2			✓		
QUENCH VALVE TEMPERATURE				1	✓		
COOLDOWN VALVE ACTUATOR	2				✓		
COOLDOWN VALVE POSITION		4			✓		
COOLDOWN VALVE TEMPERATURE				2			
RECOOLER VALVE ACTUATOR			1		(✓)		
RECOOLER VALVE POSITION				1	(✓)		
RECOOLER LIQUID LEVEL				1	(✓)		
RECOOLER INLET TEMPERATURE				1	(✓)		
RECOOLER OUTLET TEMPERATURE				1	(✓)		
SINGLE PHASE RELIEF VALVE TEMPERATURE				2	✓		
SINGLE PHASE RETURN RELIEF VALVE TEMPERATURE				2	✓		
GH ₂ RETURN RELIEF VALVE TEMPERATURE				2	✓		
20 K H ₂ RELIEF VALVE TEMPERATURE				2	✓		
LN ₂ RELIEF VALVE TEMPERATURE				2	✓		
GN ₂ RELIEF VALVE TEMPERATURE				2			
SINGLE PHASE PRESSURE				2	✓		
SINGLE PHASE RETURN PRESSURE				2	✓		
GH ₂ RETURN PRESSURE				2	✓		
20 K H ₂ PRESSURE				2	✓		
LN ₂ PRESSURE				2	✓		
GN ₂ PRESSURE				2			
CEPL COOLING VALVE ACTUATOR	1						
CEPL COOLING VALVE POSITION		1					
QUAD BP LEADS VALVE ACTUATOR	1						
QUAD BP LEADS VALVE POSITION		2					
DIPOLE BP LEADS VALVE ACTUATOR	1						
DIPOLE BP LEADS VALVE POSITION		2					
LN ₂ ISOLATION VALVE ACTUATOR	2				✓		
LN ₂ ISOLATION VALVE POSITION		4			✓		
					✓		
COOLDOWN VALVE ACTUATOR LINES 2, 3, 4, 5, 6	5				✓ (5)		
COOLDOWN VALVE POSITION LINES 2, 3, 4, 5, 6		10			✓ (5)		
COOLDOWN TEMPERATURE LINES 2, 3, 4, 5, 6				5			

Figure 35. Cryogenic Equipment and Instrumentation for SPRB.

	DO	DI	AO	AI	SCDR	
QUENCH VALVE ACTUATOR	1				✓	
QUENCH VALVE POSITION		2			✓	
QUENCH VALVE TEMPERATURE				1	✓	
COOLDOWN VALVE ACTUATOR	1				✓	
COOLDOWN VALVE POSITION		2			✓	
COOLDOWN VALVE TEMPERATURE				1		
RECOOLER VALVE ACTUATOR			1		(✓)	
RECOOLER VALVE POSITION				1	(✓)	
RECOOLER LIQUID LEVEL				1	(✓)	
RECOOLER INLET TEMPERATURE				2	(✓)	
RECOOLER OUTLET TEMPERATURE				2	(✓)	
SINGLE PHASE RELIEF VALVE TEMPERATURE				1	✓	
SINGLE PHASE RETURN RELIEF VALVE TEMPERATURE				1	✓	
GH ₂ RETURN RELIEF VALVE TEMPERATURE				1	✓	
20 KH ₂ RELIEF VALVE TEMPERATURE				1	✓	
LNG RELIEF VALVE TEMPERATURE				1	✓	
GN ₂ RELIEF VALVE TEMPERATURE				1		
SINGLE PHASE PRESSURE				1	✓	
SINGLE PHASE RETURN PRESSURE				1	✓	
GH ₂ RETURN PRESSURE				1	✓	
20 KH ₂ PRESSURE				1	✓	
LNG PRESSURE				1	✓	
GN ₂ PRESSURE				1		
CEPL COOLING VALVE ACTUATOR	1					
CEPL COOLING VALVE POSITION		1				
BP LEADS VALVE ACTUATOR	1					
BP LEADS VALVE POSITION		1				
LNG ISOLATION VALVE ACTUATOR	2				✓	
LNG ISOLATION VALVE POSITION		4			✓	
					✓	

Figure 36. Cryogenic Equipment and Instrumentation for an Isolated Cryostat, including an SPRT and SPXU.

Figure 37. Empty Cryostat: (a) Cross Section and (b) Flow Scheme.

2.3.8 Cryogenic Bypass Transfer Lines (CBTL)

Cryogenic bypass transfer lines (CBTLs) route the cryogens and superconducting buses around various warm equipment in the HEB tunnel, such as warm magnets, scrapers, injection transfer lines, and rf cavities. The bypasses also serve various isolated superconducting magnets between warm equipment in the HEB ring. A total of 1300m of bypass lines, containing the six cryogen lines, will be installed in the HEB. The CBTLs include standard 13.2-m modules (BPCR), end boxes (BPEB), where the connections to the magnet strings are made, and T-boxes (BPTB), where "T" connections are needed to feed the isolated cryostats.

CBTLs are required along the H10, H20, H40, H50, H60, and H80 straight segments. At H20, H40, H60, and H80, the bypass transfer lines are designed to cover the straight segment length between the dispersion suppressor cells, a distance of approximately 200 m. At H50 the bypass transfer line is designed to cover an 111-m-long portion of the straight segment between the dispersion suppressor cells. At H10 the bypass transfer line is designed to cover the whole length of the straight segment, plus a portion of the dispersion suppressor cells, for a total length of 482 m. The detailed design of the lattice and the bypass transfer line configuration is given in the HEB Level 3B Specification.¹

2.3.8.1 Standard and Special Bypass Cryostats (BPCR and BPCR-S)

The standard bypass cryostat (BPCR) module is the basic building block of the bypass transfer line. It provides an insulating vacuum and contains the six cryogen lines. The superconducting bus is routed through the single-phase helium supply line. Provision must be made for bus expansion and contraction during cooldown and warm-up. The standard BPCR module has a slot length of 13.171 m, including the interconnect, and an outer diameter of approximately 450 mm. A cross section view of the HEB bypass cryostat is shown in Figure 38.

In addition to the standard bypass cryostats, a number of shorter bypass cryostats are needed to match the total bypass or section lengths dictated by the lattice requirements. These special units (BPCR-S) are identical to the standard bypass cryostats in cross section and simply differ in slot length. Those BPCR-S that are shorter than 3 m are designed without the bus expansion loop.

2.3.8.2 Connection Boxes BPEB and BPTB, and Tube Sets

Two types of connection boxes are needed in the bypasses: Bypass End Boxes (BPEB), and Bypass T-Boxes (BPTB).

Bypass End Boxes (BPEB), located at the ends of a bypass, allow the cryogenic and bus connections between the bypass and the magnet strings (Figure 39). End Boxes are classified as Left and Right based on the particular end of the bypass. The BPEB insulating vacuum is isolated from the ring vacuum by a specific vacuum barrier. The end boxes contain cryogenic measurement devices, relief and cooldown valves, and vacuum instrumentation.

Tube sets are needed to make the connections between the bypass connection boxes and the corresponding spools in the magnet strings. For the BPEB the tube set is composed of six cryogenic lines, with the following size requirements:

Line 1: 4-K LHe feed with the superconducting bus; $\Phi 50$ mm nominal.

Line 2: 4-K LHe return; $\Phi 50$ mm nominal.

Line 3: 4-K GHe return; $\Phi 110$ mm nominal.

Line 4: 20-K He return; $\Phi 90$ mm nominal.

Line 5: 80-K LN₂; $\Phi 57$ mm nominal.

Line 6: 80-K GN₂ return; $\Phi 57$ mm nominal.

Bypass T-Boxes (BPTB) accommodate cryogenic and bus connections between the bypass and various isolated superconducting magnets (Figure 40). The BPTB insulating vacuum is also isolated from the ring vacuum by a vacuum barrier. Bypass T-Boxes may also contain in-line vacuum barriers.

For the BPTB the tube set is also composed of six cryogenic lines, with the following size requirements:

Line 1: 4-K LHe Feed with the superconducting bus; $\Phi 50$ mm nominal.

Line 2: 4-K LHe Return, with one superconducting bus; $\Phi 50$ mm nominal.

Line 3: 4-K GHe return; $\Phi 25$ mm nominal.

Line 4: 20-K He return; $\Phi 25$ mm nominal.

Line 5: 80-K LN₂; $\Phi 57$ mm nominal.

Line 6: 80-K GN₂ return; $\Phi 57$ mm nominal.

Figure 38. Bypass Cryostat Cross Section (Minimum Expected External Diameter 450 mm).

Figure 39. HEB Bypass End Box Connection.

Figure 40. HEB Bypass T-Box Connection.

3.0 HEAT LOAD BUDGETS AND REFRIGERATION PLANT CAPACITIES

3.1 Component Heat Load Budgets

Heat transfer into the components at liquid helium temperature is minimized by two thermal shields maintained at 84 K and 20 K, and by an insulating space maintained at high vacuum. Heat input to the 4-K components can be defined as the sum of two loads, dynamic and static. The major portion of dynamic load is caused by ramping heat loads together with eddy current losses (approximately 1 W/m). Static load results from the heat conduction and thermal radiation loads from the warmer parts in the cryostat. The total heat load is removed from the 4-K components by circulating single-phase 4-K helium through these components and by recooling this single-phase stream in recoolers along the string.

The heat load from the 4-K components is reflected as a 4-K refrigeration load on the helium plant. Some components that protrude from the outside into the 4-K parts of the cryostat, such as electrical leads, are cooled by small streams of 4-K helium; this helium is returned warm to the plant and translates into a liquefaction load on the helium plant.

The temperature of the 20-K shield is maintained by circulating 3-bar helium gas through the shield at a supply temperature of 14 K. Heat into the 80-K shield is removed by an independent nitrogen cooling system. The heat loads of the various equipment are budgeted to one of three loads on the helium refrigeration system—that is, the 4-K refrigeration load, the liquefaction load, and the 20-K shield load. The 80-K loads are budgeted to the nitrogen cooling system.

The heat budgets for the various ring components—including various magnets, spools, empty cryostats, and bypass equipment—are summarized in Table 8. Also listed in Table 8 is the heat load for a full cell (see Figure 3), which is important in sizing the helium recoolers. Details of the static and dynamic loads for these components are presented in the Appendix.

3.2 Distribution Heat Loads

Distribution heat loads are static loads associated with the equipment supplying the cryogens from the refrigerator to the ring. These include the vertical and horizontal transfer lines, the surface and tunnel distribution boxes, cold compressor, auxiliary box, and pump boxes. Table 9 gives the heat load allocations (per unit length) for the vertical and horizontal transfer lines. Table 10 gives the overall distribution loads associated with each helium plant.

Table 8. Ring Component Heat Load Budgets.

	Liquif. (g/s)	4 K Static (W)	4 K Dynamic (W)	4 K Total (W)	20 K Total (W)	80 K Total (W)
HDM		0.46	12.73	13.19	5.61	41.18
HQM		0.30	2.01	2.30	1.90	13.53
HQM1		0.29	1.30	1.59	1.77	12.47
HQM2		0.30	1.57	1.87	1.82	12.88
HQM3		0.30	2.67	2.97	2.02	14.53
HQM4		0.30	3.77	4.08	2.22	16.19
EC 6.5 m		0.32	0.32	0.64	2.80	20.98
SPXA	0.072	2.63	0.29	2.92	14.85	53.67
SPRA	0.072	2.73	0.29	3.01	15.71	57.87
SPRF/SPRI/SPRE	1.728	39.63	0.66	40.28	39.63	242.34
SPXU	0.012	0.67	0.26	0.93	7.97	23.14
BPCR 13.2 m		0.13	0.08	0.21	3.48	26.86
BPEB+CBEB		4.13	0.08	4.21	15.47	166.80
BPTB+CBTB		3.79	0.08	3.87	12.78	143.80
Full-Cell	0.144	7.81	55.50	63.31	56.8	303.32

Table 9. Transfer Line Heat Loads.

	4-K Load	20-K Load	80-K Load
Shaft Transfer Line	0.4 W/m	0.4 W/m	3.0 W/m
Horizontal Transfer Line	0.3 W/m	0.3 W/m	2.0 W/m

Table 10. Sector Distribution Loads.

	Liquif. (g/s)	4 K Total (W)	20 K Total (W)	80 K Total (W)
Helium Refrigerator – LN ₂ precooling				30 000
Helium Storage	0.8			800
Surface Distribution Box & Interfaces		60	50	400
Helium Pump Box & Interfaces		60		400
Transfer Lines, Bends & Interfaces		120	100	600
Cold Compressor System		150	50	600
Tunnel Distribution Box & Interfaces		100	50	600
Auxiliary End Box & Interfaces		100	50	400
LN ₂ Pump Box				2400
Utilities				3800
Quench and Cooldown Recovery	3.5			
Performance and Control	1.5	500	800	2000
Total Sector Distribution Loads	5.8	1090	1100	42 000

3.3 String and Sector Heat Loads and Plant Capacity Requirements

The string heat loads are calculated by summation of the static and dynamic loads of all the ring components connected to the same feed. The sector heat load is composed of the heat loads for the two strings in an HEB cryogenic sector, plus the distribution loads of the sector. Table 11 lists the static and dynamic heat loads for the two strings of the H₂O sector and the total heat load for the H₂O plant.

Table 11. H₂O Plant Total Heat Loads and Capacity Requirements.

	Liquif. (g/s)	4 K Total (W)	20 K Total (W)	80 K Total (W)
Static Heat Load—Strings	18	850	5000	29 500
Dynamic Heat Load—Strings		3660		
Distribution Loads	6	1090	1100	42 000
Unallocated	12	0	3900	8500
H ₂ O Plant Total Load	36	5600	10 000	80 000
H ₂ O Plant Design Load (Capacity Requirement)	45	6750	15 000	80 000

The refrigeration system is designed with a specific capacity to meet the various normal loads, all the loads during specific upset conditions, and the redundancy requirements. The system is able to reach its maximum design capacity, given in Table 11, when all of its components are functioning properly.

In the event of failure of any single expander, the system must continue to operate with at least the steady-state capacity given in Table 11. Also, when the other sector needs assistance in the form of liquefaction load or other loads, the refrigerator must turn up to provide this assistance. Due to the flow-rate limitations of the cold piping in the magnet strings, it is difficult to transfer 4-K refrigeration between

sectors. However, liquefaction and 20-K loads can be transferred relatively easily by shifting the warm gas flow from one sector to the other. The extra capacity also allows for quick recovery after a quench in a sector. During and after a quench the inventory and recovery process must quickly be handled. The plant has to be turned up to handle this transient.

The plant is operated in the minimum capacity mode when the sector heat loads are low for long-term cold storage of the ring. The plant is capable of operating between maximum capacity and the minimum capacity obtainable without bringing a compressor or expander off-line. In this capacity range the gas management and coldbox control schemes are capable of allowing the plant to turn up and to turn down according to the demands of the load. At lower load demands, one or more compressors and/or expanders may be shut down for efficient operation of the plant.

3.4 Nitrogen Heat Budgets

The heat loads for the nitrogen system are composed of the tunnel loads and the surface loads.

3.4.1 Tunnel Heat Loads

The 84-K shield and the LN tunnel system are designed to prevent direct infrared radiation from the 300-K shield to the 20-K shield and to intercept the heat conducted through the supports and other connections between the warm and cold components. Heat intercepted at a level of 84 K compared to the same amount of heat intercepted at a level of 20 K requires less than one-fifth of the ideal work. The 84-K shield heat load and the 20-K shield heat load used for the budget calculations are based on two MLI blankets, each with 32 layers on the 84-K shield. The detailed budgets for the 84-K shield heat loads of various ring components are given in Table 8.

3.4.2 Surface Loads

The GN_2 generated in the tunnel is used in the surface refrigeration system for helium precooling. The SRS is designed to use additional liquid nitrogen for the 300K to 80-K cold box. The total flow of LN_2 results from trading off the operating cost of the nitrogen system and the installation and operation of the helium system.

Figure 41 is a diagram of the nitrogen system heat loads and the associated mass flow rates.

Figure 41. Nitrogen System Heat Loads and Mass Flow Rates for the HEB.

4.0 FLOW AND THERMAL CHARACTERISTICS

4.1 Pressure Drop Allocations and Minimum Line Sizes

The normal operating pressure level for the single-phase helium supply and return was chosen as 0.4 MPa in order to maintain supercritical flow everywhere in the system. This includes the flows in the transfer lines from or back to the surface. The pressure level in line 4 has to be lower than the lowest pressure in lines 1 and 2 to prevent leakage or flow from line 4 to line 1 through the quench valves under normal operation. The pressure in line 4 is not allowed to fall below 0.25 MPa in the tunnel to support the pressure drops in the surface refrigeration plant. These constraints on the pressure, together with the nominal helium flow rate of 100 g/s in lines 1 and 4, determined the nominal pressure drop allocations for the tunnel components. The minimum line sizes to support these pressure drop allocations are presented in Table 12, together with the nominal pressures, temperatures, and flow rates in each of the cryogenic lines.

Table 12. Minimum Line Sizes, Nominal Conditions, and Pressure Drop Allocations.

	Line 1 4 K He Supply	Line 2 4 K LHe Return	Line 3 4 K GHe Return	Line 4 20 K He	Line 5,6 80 K LN ₂ *
Minimum Line ID (m)		0.0452	0.110	0.0824	0.0572
Nominal P (MPa)	0.4	0.3	0.085	0.25	0.5
Nominal T (K)	4.05	4.3	4.3	20	84
Nominal Density (kg/l)	0.140	0.133	0.0012	0.060	0.780
Nominal Flow (g/s)	100	60.5	68.5	100	750
Pressure Drop Allowance (Pa)					
HDM	106.4	26.6	3.42	70.0	222
HQM	31.9	5.0	0.65	13.0	42
HQM1	28.4	3.6	0.46	9.0	30
HQM2	30.1	4.1	0.53	11.0	35
HQM3	36.3	6.3	0.82	17.0	53
HQM4	41.7	8.5	1.10	23.0	71
SPXA	106.0	7.0	1.00	19.0	62
SPRA	406.0	7.0	1.00	19.0	62
EC-6.585 m	67.0	15.0	2.00	40.0	122
Bypass Cryostat-13.2 m	134.0	30.0	4.00	80.0	243
Interconnect	4.0	2.0	0.30	5.0	20

*Lines 5 and 6 are identical in diameter. The nominal pressure, temperature, and flow rates presented are for line 5, but they can also be applied to line 6 for line size and pressure drop calculations.

With the exception of line 4, the minimum line sizes are the same as in the collider. The recooler bath temperatures in the HEB are limited to 3.85 K to 4.05 K. This defines the range of pressures in line 3 (0.085 MPa minimum at the suction to the cold compressor). Due to the higher heat load in the HEB, the boil-off per cell and the total vapor flow are higher than those in the collider. This requires a larger diameter for the 4-K vapor return line. The minimum ID for line 4 in the HEB is set at 110 mm (compared to 86 mm in the collider). Figure 42 shows the results of a trade-off study between pressure drop and line size. Lines 5 and 6 are identical in diameter. The nominal pressure, temperature, and flow rates in Table 12 are for line 5, but can also be applied to line 6 for line size and pressure drop calculations.

DIAMETER	DP KPascals	DIAMETER	DT mK
90	12.17	90	151.4
100	7.45	100	90.7
110	5.029	110	60.7
120	3.689	120	44.3
130	2.899	130	34.7
140	2.413	140	28.8
150	2.1	150	25.1

Figure 42. Line Size vs. Pressure Drop Trade-off for Line 3 in the HEB.

4.2 Flow Rates and Configurations for Normal Operation

The flow configurations and the corresponding flow rates in the cryogen lines vary, depending on the mode of operation. Figure 43 shows the flow configurations in the cryogen lines for normal operation. The corresponding pressures, temperatures, and flow rates for normal operation under the full design heat load (with the beam on) are given in Table 13. The flow rates in lines 1–3 for normal operation under the standby heat load and the full design heat load are shown in Table 14. The line-1 helium temperature variations in the different coldmass passages of the magnets over a full-cell are shown in Figure 44. The calculations are based on 100 g/s of flow, full design heat load, and crossflow scheme to cool the dipole magnets.

Figure 45 shows the flow configurations in the cryogen lines when one of the two plants (H60 in this example) is down. The flow rates required in lines 1–3 for operation with the H60 plant down under the standby heat load and the full design heat load are shown in Table 15. The total heat load of the HEB (2×5600 W) cannot be handled by a single refrigeration plant. Therefore, the HEB cannot be operated under full dynamic load when one plant is down.

The flow configurations for other modes of operation are discussed in Section 5.0.

4.3 Cryogen Inventory

Fluid inventory data is crucial information for system analysis, especially in response to fast disturbances or when large quantities of cryogens have to be shifted from the surface to the ring or vice versa.

Fast disturbances such as quenches (*e.g.*, the quench of a half- or full-cell) require a quick response, but usually do not involve large amounts of cryogens. Following a full-cell quench, about 100 kg of helium may have to be shifted from line 1 to line 4 within 50–60 s, and then to the surface. A larger-scale quench such as a full-section quench, may involve up to 1200 kg of helium within 50–60 s of the quench. A line rupture may not require as fast a response as a quench, but it may affect the whole helium inventory of full string (about 4700 kg). Changes in the state of the system, such as warm-up or cooldown, also require large quantities of cryogens to be shifted from the surface to the ring or vice versa.

As a general rule the fluid inventory is a design parameter for each ring component that has to be minimized. The optimization should consider the pressure drop and heat budget allocations as well as structural constraints. Table 16 shows the HEB cryogen inventory for each component family and the summaries for the section, string, and sector inventories. Because some of the components are still in the design stage, the inventory is defined here as a “budget” value and not as an optimized value.

4.4 Sector Heat Capacity

The heat capacities of the ring components and of the sector as a whole are important in determining the time constant of the HEB for processes that involve cooldown and warm-up of the coldmasses and the shields. The material mass and thermal properties determine the heat capacity. Table 17 lists the iron mass (coldmass) for the various components and for the short and long sections. The stainless steel and aluminum masses for the 20-K and 80-K shields are also listed in Table 17.

Figure 46 presents the enthalpy of iron as a function of temperature, which is used to determine the heat capacities for the coldmasses. Figure 47 shows the coldmass enthalpy as a function of temperature for the long section and for a full sector. The combined thermal masses of the aluminum shields and the stainless steel pipes attached to the shields make up the heat capacity of the shields. Figure 48 shows the heat capacities of the 20-K and 80-K shields for a long section and for a full sector.

The data presented in Figures 47 and 48 can be used to determine the process time, flow, and refrigeration requirements. Consider cooldown of a sector coldmass, from 300 K to 80 K, for example. The heat capacity of a sector coldmass between 80 K and 300 K is $1.9\text{E}11$ J. If 200 g/s of helium flow is used (100 g/s for each string), the time required for cooldown is approximately 10 days:

$$\begin{aligned}\text{Cooldown Time} &= Q_{80 \text{ K to } 300 \text{ K}} / (\dot{m} c_p \Delta T)_{\text{He}} \\ &= (1.9\text{E}11 \text{ J}) / (0.2 \text{ kg/s} * 5200 \text{ J/kg-K} * (300-80) \text{ K}) \\ &= 8.3\text{E}5 \text{ s} \\ &= 231 \text{ h} \\ &= 9.5 \text{ days.}\end{aligned}$$

The amount of liquid nitrogen to be supplied to the refrigerator to perform this cooldown is about 480 tons, or 5 truckloads per day (assuming 10-ton trucks). For simplicity, this example did not include the shields, which will impose additional time and energy requirements.

Figure 43. Flow Configurations in the HEB for Normal Operation.

Table 13. Flow Conditions for Normal Operation.

		TOTAL LENGTH 10800. m.									
		NORTH - WEST HEB/2 5400m					SOUTH - EAST HEB/2 5400m				
		STRING1 CCW			STRING2 CW		STRING1 CCW			STRING2 CW	
		H8	H1	H2	H3		H4	H5	H6	H7	
		1104 m	1628 m	1334 m	1334 m		1436 m	1296 m	1334 m	1334 m	
		H 80	H 10	H 20	H 30		H 40	H 50	H 60	H 70	H 80
4K	SLOAD W	175	260	205	205		230	205	205	205	
	DLOAD W	725	1075	930	930		950	850	930	930	
	LIQ g/s	4.6	4.6	4.6	4.6		4.6	4.6	4.6	4.6	
	P MPa	0.356	0.4	0.4	0.36		0.358	0.4	0.4	0.36	
	DP KPa	18	26	20	20		23	19	20	20	
	Tin K		4.05	4.05				4.05	4.05		
	Tmax K	(Tmaxmax=4.05+dt(ce))=4.22)				4.05	4.05				4.05
	M g/s	100	100	100	100		100	100	100	100	
4K RET	P MPa	0.35			0.35		0.35				0.35
45.2mm	Pmin MPa										
I.D.	Tin K	4.3			4.3		4.3				4.3
	M g/s	100	79		100		100	79		100	
4K V	Pmin MPa		83	83				84.5	84.5		
110 mm	Pmax MPa	85			85		85				85
I.D.	TSAT K	4.005	4.023	4.023	4.005		4.005	4.023	4.023	4.005	
T = 4.3 K	DT K	18 mK		18 mK			18 mK		18 mK		
	M g/s	0	43	107	109	54	0	57	107	109	54
		to account for bellows, bends and U tubes: increase pressure drop per sector by 0.6 kPa									
20K	LOAD W	1045	1540	1220	1220		1285	1155	1220	1220	
82.6mm	P MPa	0.225	0.214	0.25	0.235		0.225	0.214	0.25	0.235	
I.D.	T K	21.9	24.1	15	17.2	19.4	21.9	24.1	15	17.2	19.4
	M g/s	100	100	100	100		100	100	100	100	
80K L	LOAD W	5950	8700	6935	6935		7680	6970	6935	6935	
57.2mm	Pmin MPa		2.2					2.2			
I.D.	T K		81					81			
	M g/s	531	500	991	954		917	877	605	568	
	DM g/s	31	45	37	37		40	36	37	37	
(to surface)	DMS g/s		16					220+16			
80K V	P MPa	0.17	0.14	0.14	0.17		0.17	0.14	0.14	0.17	
57.2mm	T K	82.1	80.3	80.3	82.1		82.1	80.3	80.3	82.1	
I.D.	M g/s	18	49	56	19		18	58	56	19	
		He boiloff: 3.0 g/s per cell									

Table 14. Helium Flows in Lines 1-3 for Standby and Normal Operation.

TOTAL LENGTH 10800. m.															
NORTH - WEST HEB/2 5400m						SOUTH - EAST HEB/2 5400m									
STRING1 CCW			STRING2 CW			STRING1 CCW			STRING2 CW						
H8		H1		H2		H3		H4		H5		H6		H7	
1104 m		1628 m		1334 m		1334 m		1436 m		1296 m		1334 m		1334 m	
H 80		H 10		H 20		H 30		H 40		H 50		H 60		H 70 H80	
(a) STANDBY MODE															
DIPOLE DYNAMIC LOAD = 0 W/m															
LOAD (W)				205 W		205 W		230 W		205 W					
BOILOFF (g/s)				9.8 g/s		9.8 g/s		11 g/s		9.8 g/s					
<div>line 1</div> <div>line 2</div> <div>line 3</div>															
(b) NORMAL OPERATION MODE															
DIPOLE DYNAMIC LOAD = 1 W/m															
LOAD (W)				1135 W		1135 W		1180 W		1055 W					
BOILOFF (g/s)				54.3 g/s		54.3 g/s		56.5 g/s		50.5 g/s					
<div>line 1</div> <div>line 2</div> <div>line 3</div>															

- a ————— Helium temperature in the annular passage
- b ———— Bulk helium temperature (calculated)
- c - - - - - Helium temperature in the main passages
- d ————— Coil temperature
- Interconnect

Figure 44. Line-1 Helium Temperature Variations over a Cell for Normal Operation.

Figure 45. Flow Configurations in the HEB with H60 Plant Down.

Table 15. Helium Flows in Lines 1-3 with H60 Plant Down.

TOTAL LENGTH 10800. m.																	
NORTH - WEST HEB/2 5400m								SOUTH - EAST HEB/2 5400m									
STRING1 CCW				STRING2 CW				STRING1 CCW				STRING2 CW					
H8		H1		H2		H3		H4		H5		H6		H7			
1104 m		1628 m		1334 m		1334 m		1436 m		1296 m		1334 m		1334 m			
H	80	H	10	H	20	H	30	H	40	H	50	H	60	H	70 H80		
(a) STANDBY MODE																	
DIPOLE DYNAMIC LOAD = 0 W/m																	
LOAD (W)				205 W		205 W		230 W		205 W							
BOILOFF (g/s)				9.8 g/s		9.8 g/s		11 g/s		9.8 g/s
				100 g/s						line 1					
						59.6 g/s				100		line 2					
						40.4		30.6		20.8		9.8		0		line 3	
(b) NORMAL OPERATION MODE																	
DIPOLE DYNAMIC LOAD = 1 W/m																	
LOAD (W)				1135 W		1135 W		1180 W		1055 W							
BOILOFF (g/s)				54.3 g/s		54.3 g/s		56.5 g/s		50.5 g/s
				100 g/s						line 1					
						115.6 g/s				100		line 2					
						215.6		161.3		107		50.5		0		line 3	
The total heat load of the HEB (2 x 5600 Watts) cannot be handled by a single refrigeration plant.																	
Therefore the HEB cannot be operated under full dynamic load when one plant is down.																	

Table 16. Helium and Nitrogen Inventories for the HEB.

										H20 SECTOR										H60 SECTOR														
										STRING 1 - CCW					STRING 2 - CW					STRING 1 - CCW					STRING 2 - CW									
										1104 m	1628 m	1334 m	1334 m	1436 m	1334 m	1334 m	1334 m	1334 m	1334 m	1296 m	1436 m	1334 m	1334 m	1334 m	1334 m	1334 m	1334 m	1334 m	1334 m	1334 m	1334 m	1334 m	TOTAL HEB	
										units	mass	units	mass	units	mass	units	mass	units	mass	units	mass	units	mass	units	mass	units	mass	units	mass	units	mass	mass kg		
										liters	kg	liters	kg	liters	kg	liters	kg	liters	kg	liters	kg	liters	kg	liters	kg	liters	kg	liters	kg	liters	kg			
										MPa	K	°C	ρ	V	liters	kg	units	mass	units	mass	units	mass	units	mass	units	mass	units	mass	units	mass	units	mass		
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
										mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm							

Table 17. HEB Iron and Aluminum Mass.

				Long section			Short section		
				1628 m			1104 m		
	diameter	length	unit mass	Number	Iron/SS	Aluminum	Number	Iron/SS	Aluminum
	mm	m	kg/m	of units	kg	kg	of units	kg	kg
MAGNETS									
HDM B		12.29	650	66	527241		60	479310	
HQM F, D		1.6	650	37	38480		32	33280	
Q1, Q3, Q4, Q5		0.902	650	8	4690				
Q2		1.173	650	2	1525				
QS1 HQM3		2.258	650						
QS2, QS3 HQM4		3.347	650						
Interconnect		0.883	50	113	4989		92	4600	
SPOOLS									
H-SPXA		3.675	300	16	17640		15	16538	
H-SPRA		3.675	300	21	23153		16	17640	
H-SPRI Short		3.675	300						
H-SPRI/F/E		7.35	300	1	2205		1	2205	
SPXA-RB		3.675	300	9	9923				
SPRA-EB		3.675	300	2	2205				
SPRA-TB		3.675	300	9	9923				
EMPTY CRYOSTATS									
H ECL		6.585	33	10	2173		7	1521	
H ECS		2.8	33	7	647		1	92	
BY PASSES									
BYPASS (m)				529 m					
BPCR-13		13	33	33	14157				
BPCR-S		6.5	33	11	2360				
BPTB		2	100	9	1800				
BPEB		2	100	2	400				
Total line 2 (+assembly=2*)	45.2		3.36	1628 m	5476		1104 m	3714	
Total line 3 (+assembly=2*)	110		8.19	1628 m	13327		1104 m	9037	
Total COLD MASS / SECTION (tons)					682			568	
Total line 4 (+assembly=2*)	82.6		6.15	1628 m	10007		1104 m	6786	
20 K shield	600		10.17	1628 m		16563	1104 m		11232
Total 20 K SHIELD / SECTION (tons)					10.0	16.6		6.8	11.2
Total line 5 (+assembly=2*)	57.2		4.26	1628 m	6930		1104 m	4699	
Total line 6 (+assembly=2*)	57.2		4.26	1628 m	6930		1104 m	4699	
80 K shield	650		11.02	1628 m		17943	1104 m		12168
Total 80 K SHIELD / SECTION (tons)					13.9	17.9		9.4	12.2

Figure 46. Iron Enthalpy as a Function of Temperature.

K	J	J
0	0.0E+00	0.0E+00
20	2.2E+07	7.9E+07
40	2.1E+08	7.8E+08
60	9.8E+08	3.6E+09
80	2.6E+09	9.6E+09
100	5.2E+09	1.9E+10
120	8.5E+09	3.1E+10
140	1.2E+10	4.5E+10
160	1.7E+10	6.2E+10
180	2.2E+10	7.9E+10
200	2.7E+10	9.8E+10
220	3.2E+10	1.2E+11
240	3.8E+10	1.4E+11
260	4.3E+10	1.6E+11
280	4.9E+10	1.8E+11
300	5.5E+10	2.0E+11

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Figure 48. Shield Enthalpy vs. Temperature: (a) 20-K Shield, (b) 80-K Shield.

5.0 PROCESS DESCRIPTIONS

5.1 Operating Modes of the Refrigeration Plant

The modes of operation for the HEB cryogenic system are defined by different states. Such states are determined by steady state temperatures, pressures, flows, or other measured parameters, and by processes, which are the required transients to change the conditions of the system to a new status. Figure 49 shows the logic diagram for the states and processes corresponding to the different operational modes of the refrigeration plants. Table 18 presents the helium and nitrogen inventories for the various states of the system, together with brief descriptions of the processes.

The two refrigeration plants for the HEB are identical in design and capacity to those for the collider. However, there are differences in the loads for each plant because of variations in sector design. The plants are designed to handle a range of capacities, including standby load, when the beam is not active; nominal load, when the beam is active; assist load, when a neighboring plant needs assistance; upset loads, in particular for quench recovery; and loads during cooldown, warm-up, and maintenance. The plants are also designed to operate in a minimum capacity mode. For the different situations mentioned above the refrigeration plant operates in different modes, defined below:

- The plant is operated in the Normal Mode when the system is at full normal operation. This means the system is cold and the beam is on. In this mode the load on the refrigeration plant may vary according to the beam intensity.
- The plant is operated in the Standby Mode when the system is cold with no beam operating, and there is no current in the magnets. In this mode, the load on the refrigeration plant depends on the static heat load.
- The plant is operated in the Assist Mode when part of its capacity needs to be transferred to a neighboring plant. In this mode, capacity is transferred by shifting cryogens through sector boundaries.
- The plant is operated in the Quench Recovery Mode after a quench is detected in a string.
- The plant is operated in one of the Utility Modes during cleanup, cooldown, warm-up, and maintenance.
- The plant is operated in the Minimum Capacity Mode when the sector heat loads are low for long-term cold storage of the ring.

5.2 Normal Operation Schemes

5.2.1 Normal Mode—Nominal Load

This is the nominal heat load expected when the beam is on and at full power. This load will vary slightly from one sector to another because of the difference in the design of the sectors. The normal operation of the HEB will be 2–3 h per day. During the remaining time the HEB will be idle, in the “standby cold” status. The HEB has a very high dynamic load compared to the collider load. Because there is only one ring in the HEB, the 20-K shield line has to be routed in a different way compared to the collider. The 20-K shield route starts at one plant and ends in the other. If inventory accumulates in one plant, the 20-K supply flows can be temporarily adjusted to return the excess inventory; otherwise, inventory can be exchanged through the warm return header. Helium from the dewar will be used during the normal operation, if necessary, and the dewar will be refilled when the system is in standby status.

If a quench occurs in one sector, the proton beam is dumped and the refrigeration system in this specific sector goes into quench recovery mode. The currents in the magnets of the other sector are ramped down to zero; its refrigerator is turned down from normal mode to standby mode during recovery in the quenched sector.

The flow conditions for normal mode of operation are given in Tables 13 and 14. The corresponding 4-K flow configuration is given in Figure 50. The 20-K flow, the 80-K flow, and the lead-cooling flow configurations are shown in Figures 51–53, respectively.

Figure 49. State and Process Diagram for the HEB Cryogenic System.

Table 18. Helium and Nitrogen Inventories for Various States of the HEB Cryogenic System.

			SECTOR TREATMENT												
			CLEANUP	WARM	80 K SHIELD	20 K SHIELD	COLDMASS	COLDMASS	COLDMASS	COLDMASS	NORMAL OPERATION				
			300 K	STANDBY	COLD	AT 80 K	AT 80 K	AT 20 K	AT 5 K		4 K				
			0.3 MPa	0.2 MPa		0.3 MPa	0.3 MPa	0.3 MPa	0.3 MPa		0.4 MPa				
			He density, kg/l	He density, kg/l	LN density, kg/l	He density, kg/l	He density, kg/l	He density, kg/l	He density, kg/l		He density, kg/l				
LONG			0.0004808	0.00032	0.78	0.001714	0.001714	0.006	0.1175		0.14				
SECTION	STRING	SECTOR	TOTAL	SECTOR	SECTOR	SECTOR	SECTOR	SECTOR	SECTOR	SECTOR	LONG	STRING	SECTOR		
VOLUME			MASS FLOW	MASS	MASS	MASS	MASS	MASS	MASS	MASS	SECTION	MASS	MASS		
LITERS			kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg		
LINE 1 4 K He FEED	17379	26750	52779	76	17	17	17	90	317	6201	2433	3745	7389		
LINE 2 4 K LHe RETURN	2611	4382	8662	12	3	3	3	15	52	1018	347	583	1152		
LINE 3 4 K GHe RETURN	15464	25951	51295	74	16	16	16	88	308	615	193	324	641		
RECOOLERS	891	1350	2538	4	1	1	1	4	15	30	125	189	355		
LINE 4 20 K	8720	14633	28922	42	9	9	30	50	174	174	52	88	174		
LINE 5 LN2	4181	7016	13867	150	33	10816	10816	10816	10816	10816	3261	5472	10816		
LINE 6 GN2	4181	7016	13867	150	33	76	76	76	76	76	23	39	76		
CLEANUP															
Required: Circulation of dry clean gas at 300 K through the whole system. Total = 5 times the volume of the system. Maximum allowed pressure 1 MPa. Expected time 2 hours.															
Final conditions: 300 K, 0.1 MPa, system is full with pure dry gas (helium in the helium system and nitrogen in the nitrogen system).															
Total amount of helium to be purified: 500 kg.															
PUMPDOWN															
Pumpdown of 5.4 km-long sector (64 cells, 65 m each + bypasses and isolated cryostats), 19.5 m ³ per cell.															
Final pressure: 1.3E-2 Pa. Expected time: 8 hours per cell, including leak checking.															
COOLDOWN 80 K SHIELD FROM 300 K TO 80 K															
Cooldown of 46.6 tons of steel and 60.2 tons of aluminum. Total of 1.38E10 J to be removed from the shield. LN2 consumption for cooldown: 35 tons. Initial flow rate per string: 20 g/s max.															
Expected time: 7 days (at an average flow of 60 g/s). 80 K LN2 which is warmed up to 300 K during cooldown is vented to the atmosphere.															
Inventory of LN2 in the lines increases from (33+33) kg to (10816+76) kg.															
COOLDOWN 20 K SHIELD FROM 300 K TO 80 K															
Cooldown of 33.6 tons of steel and 55.6 tons of aluminum. Total of 1.25E10 J to be removed from the shield. Helium consumption for cooldown (80 K helium warmed up to 300 K): 35 tons.															
Initial flow rate per string: 20 g/s maximum. Expected time: 2 days (at an average flow of 60 g/s)															
COLDMASS COOLDOWN FROM 300 K TO 80 K															
Cooldown of 2700 tons of iron: Total of 1.9E11 J to be removed from the cold mass. He consumption for cooldown (80 K helium warmed up to 300 K): 166 tons.															
Average flow rate per string: 100 g/s. Expected time: 10 days. Increase the He inventory in the system from 86 kg to 247 kg.															
Nitrogen consumption in the SRS for the coldmass cooldown: 475 tons.															
COLDMASS COOLDOWN FROM 80 K TO 20 K															
Cooldown of 2700 tons of iron: Total of 9.6E9 J to be removed from the cold mass. He consumption for cooldown 30.5 tons of 20 K He. 20 K helium returns to the refrigerator at 80 K.															
at an average flow rate per string: 70 g/s. Expected time: 60 hours. Increase the He inventory in the system from 247 kg to 865 kg.															
COLDMASS COOLDOWN FROM 20 K TO 4-5 K															
Cooldown of 2700 tons of iron: Total of 7.7E7 J to be removed from the cold mass. He consumption for cooldown: 755 kg of He at 4 K, 0.3 MPa warmed up to 20 K.															
at an average flow rate per string: 100 g/s. Expected time: 10-12 hours. Increase the He inventory in the cold mass from 865 kg to 8038 kg (at 5 K).															
FILLUP															
Activation of recoler temperature control loops: 295 Kg LHe transferred to fill the recoolers: increase the He inventory in the system from 8038 kg to 9711 kg.															
Final Conditions: System in "Standby/Ready" Status.															
STANDBY COLD															
The system is cold and ready for beam injection. The heat load is static only. 4 K helium is supplied through line 1 at 200 g/s per sector. Line 2 serves for 4 K LHe return.															
Expected vapor return per sector 41 g/s.															
NORMAL OPERATION															
The system is cold and the beam is on. The heat load is static plus dynamic. 4 K helium is supplied through line 1 at 200 g/s per sector. Additional 16 g/s is supplied through line 2.															
Expected vapor return per sector 216 g/s.															
QUENCH															
The expected amount of energy released when a cell is quenched is 5 MJ. During the first 30 seconds 1/3 of this energy is transferred to the helium in line 1. The helium in the quenched cell is warmed to 20 K and pressurized to a maximum of 0.12 MPa. It is expected that the inventory will be reduced from 90 kg per cell to 20 kg in the first 30 seconds. Final conditions: after relieving the He inventory the quench valve closes, and the 4 K and 20 K flows are reestablished. Duration: 2 hours to cool down the system back to 4 K and activate the normal operation control loops.															
EMPTYING															
Initial conditions: Standby Cold. The emptying process is performed for a whole string. 20 K helium is pumped into line 1 through a quench valve and the 4 K helium is forced back to the dewar on the surface.															
WARMUP															
Warmup processes from 4 K to 20 K, from 20 K to 80 K, and from 80 K to 300 K are performed individually for each section.															
GAS DESORPTION															
Gas desorption involves emptying and warmup of the strings from 4 K to 20 K. Warmup to above 20 K may also be necessary.

Figure 50. HEB Cryogenic System—Normal Operation 4-K Helium Supply through Line 1 and Line 2.

Figure 51. HEB Cryogenic System—20-K Refrigeration Loop.

Figure 52. HEB Cryogenic System—84-K Refrigeration Loop.

Figure 53. HEB Cryogenic System—Lead Cooling Loop.

5.2.2 Standby Mode—Standby Load

When the HEB ring is cold with no beam and no current, the only refrigeration heat loads are reduced to the static conduction and thermal radiation loads only. Flow through the leads is also decreased, reducing the liquefaction loads from 36 g/s to about 25 g/s. The refrigeration system is operated in its standby mode.

The flow conditions for standby mode of operation are given in Table 14. The 4-K flow configuration for this case is given in Figure 54. The 20-K flow, the 80-K flow, and the lead-cooling flow configurations are the same as in the normal mode of operation.

5.2.3 Assist Mode—Assist Load

In the event of a more serious failure in one of the sectors (*e.g.*, more than one expander failure), such that its refrigerator could not handle the nominal operating loads, the other plant could be turned up to its maximum capacity to take the liquefaction loads and 20-K loads from the sector requiring assistance. Part of these loads may also be taken up by the collider N15 plant through the collider-to-HEB transfer line.

The assist mode for the HEB plants is of lesser importance than for the collider, since the normal operation of the HEB is only 2–3 h per day, which allows sufficient time for the system to recover—*i.e.*, to liquefy warm gas and refill the dewars, *etc.*

5.2.4 Quench and Recovery Mode

The quench protection system is designed to dump the stored energy into specific energy dumps in the event of a quench. However, some of the half-cell stored energy is dissipated in the magnet windings, causing them to warm up. When a quench is detected in any magnet, a quench is induced in the entire full cell (65 m) for protection. The cell-stored energy of roughly 5 MJ is divided between the helium and coldmass, with about one-third of this energy going to the helium during the first 30 s. As the temperature and pressure of the helium increase, the inventory of the cell, equivalent to roughly 650 l, must be absorbed by the SRS in a few minutes to relief the system. The quench detection system opens the quench relief valves to vent the warm helium to the 20-K shield line; otherwise, the warm helium flow may induce a quench in the rest of the string. If many cells quench at a given time, the temperature in the 20-K line drops and the pressure rises. This low-temperature helium returns through the 20-K return line to the plant, exchanging heat with the 20-K feed flow. The rising suction pressure on the 20-K compressor increases its mass flow throughput, thus aiding the quench recovery and inventory management associated with the quench process. The 20-K compressor and its gas management operate with varying suction pressure, nominally between 2 bar and 4 bar. The 4-K helium loop provides the additional inventory for cooling and filling of the magnets back to the normal operating condition. As the quenched section is cooled back down, helium vents from the coldmass through the quench valve into the 20-K line until it reaches normal operating temperatures. The remainder of the 5-MJ energy per cell is removed from the coldmass during this recovery period. Excess inventory that cannot be reliquefied goes to the warm storage. When the single-phase return flow is not sufficient because of depletion during the recovery period, liquid from the dewar is used to aid subcooling in the surface precooler. The plant is able to absorb the 5 MJ released by one cell in approximately 2 h.

The flow configuration for the quench recovery mode is given in Figure 55. The quench recovery process involves both HEB refrigerators in absorbing and shifting the helium inventory from the quenched string. The balance of the flows in the refrigerators during quench transients requires further analysis. Simulations of local helium venting in the magnet strings for various stages of a quench are given in References 10–12 and 39.

Figure 54. HEB Cryogenic System—Standby-Ready 4-K Helium Supply through Line 1 Only.

Figure 55. Cryogenic System for the HEB—Quench and Recovery.

5.2.5 Maximum Capacity Modes

In maximum capacity mode the full set of compressors is running. When warm gas has to be liquefied from external delivery, the refrigerator operates in maximum liquefaction mode. When cold gas has to be processed during external liquid delivery, the refrigerator operates in maximum refrigeration mode. When the system is at 20 K, the refrigerator operates in maximum 20-K refrigeration mode. Any combination of these modes may be needed:

- Maximum liquefaction mode for full (100%) liquefaction capacity
- Maximum refrigeration mode for full refrigeration capacity
- Maximum 20-K refrigeration mode for full (100%) 20-K refrigeration capacity.

5.2.6 Minimum Capacity Modes

When 4-K cooling of the magnet strings is not required for a prolonged period of time—during repair, maintenance, and cold storage of the collider rings at 80 K or 20 K—the plant runs at a minimum capacity. That is, it runs with a minimum set of compressors, one first and one second stage, to process boil-off from the dewar and to keep the 20-K shield cold. One or more expanders may be shut down to run in this mode. In this minimum capacity arrangement, the plant must be able to operate in full liquefaction mode, full refrigeration mode, and any liquefaction/refrigeration (mixed) ratio mode.

5.3 Utility Modes and Maintenance Operations

The following utility modes and maintenance operations are described in this section. The corresponding process diagrams are included at the end of the chapter.

- Cleanup
- Pumpdown
- Sector cooldown
- System warm-up
- Section repair.

5.3.1 Cleanup

Initial commissioning of the HEB requires the circulation of clean, warm helium gas through the magnet strings and associated equipment to remove contaminants, particularly moisture and residual gases in the windings and piping. The 20-K compressor is used for this purpose. The warm, clean gas is supplied to the magnet string and the various helium flow loops through the cooldown supply line. The return flow is routed directly to 20-K compressor suction. Molecular sieve adsorber beds in the compressor suction line remove moisture and contaminants. The dryer bed design shall be verified for operation at these flow and pressure conditions.

The cleanup process is performed prior to cooldown of the HEB from 300 K down. The whole system is warm, and the lines are full of dry air. Before the warm circulation process is initiated, the system is purged, evacuated, and charged with helium.

The 20-K compressor is used for this purpose with appropriate suction pressure (2–4 bar nominal) and outlet at the system design pressure to provide up to 200 g/s of 300-K helium flow. The helium flows through the high-pressure side of coldbox heat exchangers HX-1A and HX-1B, and the 80-K adsorber bed requiring availability of LN₂. The helium is then bypassed to the medium-pressure circuit of HX-1A (via V-1351) at the operating pressure for warmup to room temperature. The high-pressure, 300-K helium is routed through valves V-1362, V-1462, and V-1506 to Line 1 in the feed spool (SPRF), while part of it may be diverted to line 2 through valve V-1503. The low-temperature coldbox is not operating. The boiloff from the dewar goes to suction of the first stage compressor. If necessary the compressors may be operated to process this gas.

There are several loops to be cleaned: the magnet string, the single-phase return, the gas helium return, the 20-K lines, the helium recoilers, the power leads, etc. The return flow has several routes:

1. The return flow is directed through the 20-K line, then through the quench relief valves located in the spool pieces, and it returns to the dehydration skid via valves V-1411 and V-1323. Figure 56 shows the cleanup process of the magnet string and the single-phase return line.
2. The return flow is directed through the warm return header, then through cooldown and lead cooling valves, and it returns to the dehydration skid through valve V-1324. Figure 57 shows the circulation process of the magnet strings and current leads.
3. The return flow is directed through the GHe return, then through re cooler valves, and it returns to the dehydration skid via valves V-1421 and V-1323.
4. The return flow may be returned through the single-phase return line and via V-1507 to the compressor.

A maximum flow rate of 100 g/s per string is available for cleanup. Flow resistance limits the flow rate through the magnet string to a maximum of 50 g/s. The flow rate through the system varies depending on the cleanup routes.

The status of the system after warm circulation is "WARM CLEAN": The cold lines and passages are at 300 K, and the quench valves, cooldown valves, and re cooler control valves are closed. The system is clean and ready for insulating vacuum pumpdown and cooldown.

The entire volume in the sector has to be circulated at least five times. The volumes of the piping and magnet flow channels are listed in Table 16. Estimated cleanup time is approximately 2 h.

5.3.2 Pumpdown

Before any cooldown processes can be initiated, the insulating vacuum chambers of the cryostats and the beam tube must be pumped down to the appropriate level of $1.3\text{E-}2$ Pa. Total insulating volume to be pumped down per sector includes the insulating space for 64 cells, plus bypasses and isolated cryostats, with a volume of approximately 19.5 m^3 per cell. Expected time, including leak-checking, is about 8 h per cell.

5.3.3 Sector Cooldown

Cooldown of the magnet strings is carried out in various phases. The supply pressures and temperatures for the various phases are given in Table 19. Although the helium refrigeration system is designed for a nominal supply of 400 g/s of helium flow for cooldown from 300 K to 80 K, the system pressure drop does not allow flow rates higher than 100 g/s per string. The system is designed to enable the control of the cooldown feed flow temperature by mixing the warm and cold helium supply (V-1362 and V-1363). Some or all of the expanders may be used in various cooldown phases. The return flow is valved into the refrigerator return side at various temperatures during successive cooldown phases. The goal is to reduce the temperatures of the different parts of the cryostat to their nominal operating values in a controlled way to achieve minimum cooldown time and minimum cooldown cost, and to prevent excessive thermal stresses.

Table 19. Coldmass Cooldown Conditions.

Starting Temp (K)	Ending Temp (K)	Supply Pressure (bar)	Return Pressure (bar)	Supply Flow rate (g/s)	Cooling Capacity (kW)	Wave Speed (m/h)	Cooldown Time (days)	Sector He Inventory (kg)
300	80	16	4	200	450	12	10	247
80	20	16	2.5	140	50	45	2.5	865
20	5	4	2.5	200	>12*	225	0.5	8038

* With liquid consumption from dewar.

Figure 56. Sector Cleanup—Warm Gas Circulation in Line 1, Line 2, and Line 4.

The following process may be applied for sector cooldown when both strings of a sector are cooled down simultaneously. The sector cooldown process may be started after the insulating vacuum has been successfully pumped down and leak-checked. A software interlock inhibits the cooldown start-up if vacuum conditions are inadequate.

The cooldown of a sector is performed in three major steps, as dictated by the refrigerator design:

- Step 1: Sector cooldown from 300 K to 80 K
- Step 2: Sector cooldown from 80 K to 20 K
- Step 3: Sector cooldown from 20 K to 4–5 K and fill.

For the first step of cooldown only the warm coldbox is operated to prevent damage to the expanders due to possible release of contamination during an upset condition. During the steps the flows of the cryogenics at different temperatures are routed in different ways. Software interlocks prevent disorder in the cooldown process.

A helium flow rate of 200 g/s at 80 K is supplied to the magnet strings, 100 g/s per string, and 332 g/s of liquid nitrogen is expended for the 80-K shield refrigeration, 166 g/s per string. The required capacity for cooling the 200-g/s warm helium to 80 K is achieved by boiling 570 g/s of liquid nitrogen. The refrigeration plant requires a continuous supply of the 570 g/s of liquid nitrogen for the helium system and the 332 g/s for the 80-K shield. (Total 3240 kg/h or 78 tons/day $\approx$ 4 trucks/day.) Sector cooldown to 80 K will take about 10–12 days.

Only the warm coldbox system is operating during this process. Liquid nitrogen is vaporized and warmed up to 300 K by heat exchange with the helium stream coming from the compressor system. For cooldown the minimum supply pressure required for the 80-K helium is 10 bar, using two compression stages. Under normal operation the warm return header is pressurized to 4 bar, and only the 20-K compressor is required to provide the 100 g/s needed. The supply pressure required can go up to 16 bar because the suction pressure is at 4 bar. If the return header cannot be pressurized to 4 bar, then the system has to be operated at lower flow rates to prevent damage to the dehydration bed. The flow exiting the 80-K adsorber beds is routed to the cooldown supply line through V-1363 and to the LHe main feed line via crossover valve V-1462. The flow bypasses the surface precooler by valve V-1508. If the precooler is still warm, it should be cooled to 80 K by opening valve V-1514, with the warm gas vented through V-1512.

5.3.3.1 Sector 80-K Shield Cooldown from 300 K to 80 K

The 80-K lines and shield should be cooled down before initiating helium cooldown of the 20-K shield and the coldmass. The 80-K shield and lines include 46.6 tons of steel and 60.2 tons of aluminum per sector; a total of 1.38×10^{10} J has to be removed from the shield by LN_2 flow through line 5 (see Table 17 and Figure 48). LN_2 is supplied to the magnet strings at the feed spool; the warm gas is removed from the magnet string at the end spool and vented to the atmosphere through the nitrogen dump tanks. Vapor generated in the N_2 recoolers during cooldown is returned to the refrigerator through line 6 for helium precooling. Figure 58 shows the nitrogen circulation process for the 80-K shield cooldown.

Initially, the LN_2 flow rate per string must be low (20 g/s maximum) to prevent thermal shocks and excessive thermal stresses. The expected cooldown time is 7 days (at an average flow of 60 g/s). This will consume 37 tons of LN_2 per sector. Inventory of LN_2 in the lines increases from 66 kg in both N_2 lines (33 kg each) to 10 816 kg in line 5 and 76 kg in line 6 at the end of cooldown.

Figure 58. Sector 80-K Shield Cooldown.

5.3.3.2 Sector 20-K Shield Cooldown from 300 K to 80 K

The next step following the 80-K shield cooldown is to cool down the 20-K shield independently to 80 K. This process is performed by using the 300–80 K coldbox, in which the helium flow is cooled using a counterflow of 80-K nitrogen. The 80-K helium is routed through crossover valves V-1461 and V-1508 and may be introduced to both strings of a sector at the feed spool. The warm gas is removed from the strings through the 20-K cooldown valves at the isolation and end spools, and is returned to the refrigerator through the warm return header. An alternative is to carry out the 20-K shield cooldown together with the coldmass cooldown, as described in the next section.

The shield cooldown should be carried out at a controlled rate to prevent excessive thermal stresses. The flow rate is controlled in the tunnel distribution box and is limited to 20 g/s per string initially. Once the 20-K shield is cold, the flow rate to the string is increased to 100 g/s, and the normal 20-K loop circulation is established (Figure 51).

The 20-K shield is composed of 33.6 tons of steel and 55.6 tons of aluminum per sector. A total of 1.25×10^9 J is to be removed from the shield. Expected time for 20-K shield cooldown is 2 days (at an average flow of 60 g/s), with a helium consumption of 35 tons (80-K helium warmed up to 300 K). The amount of nitrogen required for this process, assuming a 90% efficiency, is 34 tons.

5.3.3.3 Sector Coldmass Cooldown from 300 K to 80 K

There are two possible ways to cool the magnet string. The first method (Figure 59) is to supply the 80-K helium at one end of the string to both the single-phase feed and single-phase return. The warm flow is returned through the cooldown valves and the warm return header to the refrigerator. The recoolers valves are kept open, and the cooldown valves are open. A cooldown wave develops and travels along the string. Cooldown valves are successively closed as the cooldown wave progresses. A small part of the flow may be diverted through the current leads and bypass leads directly to the warm header. The quench valves may be opened to cool the 20-K shield at the same time. To prevent excess thermal stresses in the system, the maximum temperature gradient in the cooldown wave should not exceed 30 K/m.

The second method (Figure 60) is to cool the magnets in parallel by supplying 80-K helium through the 20-K lines. There are one cooldown valve and two quench valves per cell. During this process, all the cooldown valves and every other quench valve are kept open. The 80-K helium supplied to the 20-K shield lines flows through the quench valves to the magnet half-cell and then through the cooldown valves into the 300-K warm return header.

The cooldown supply temperature can be controlled by mixing warm gas through V-1361 and V-1362 with cold gas supplied from V-1363.

Total energy to be removed from a sector (2700 tons of coldmass) is 1.9×10^{11} J. At an average flow rate of 100 g/s per string, cooldown is expected to take about 10 days for a 2700-m-long string. The helium consumption for cooldown (80-K helium to be warmed up to 300 K) is 166 tons. Nitrogen consumption in the refrigerator for the coldmass cooldown to 80 K is 475 tons. If cooldown is done in parallel, 80-K helium can be supplied to the coldmass through the quench valves at a rate of 200 g/s per string. Assuming the flow is distributed uniformly to each cell, the cooldown time can be reduced to approximately 5 days.

The status of the system after cooldown to 80 K is "COLDMASS AT 80 K." The 80-K shield is refrigerated by nitrogen at a nominal flow rate. Cooldown valves, quench valves, and re cooler valves are closed. All parts of the string are at 80 K, at a pressure of 0.3 MPa, and the 20-K shield is at 80 K. No flow is required in the coldmass. The helium inventory in a sector is about 247 kg.

Figure 59. Sector Coldmass Cooldown from 300 K to 80 K—Serial Cooldown.

Figure 60. Sector Coldmass Cooldown from 300 K to 80 K—Parallel Cooldown.

5.3.3.4 Sector Cooldown to 20 K

The cooldown process from 80 K to 20 K is designed to be performed in one step. However, if necessary, there is the capability to perform this cooldown in multiple steps by mixing 20-K helium with warmer gas. High-pressure, 15–20-K gas from V-1443, through the cooldown supply line, is fed to the main single-phase feed line. The magnet string, the 20-K shield, the 4-K return line, and the GHe return line are cooled down from 80 K to 20 K during this process.

For 80-K to 20-K cooldown the available cooling capacity is about 50 kW, defined by the expander capacity. Supply of 140 g/s of helium (70 g/s per string) at approximately 15 K and at high pressure is available from the high-pressure tap through valve V-1443, located below the third expander. The cold flow is supplied to the single-phase feed line through valves V-1462 and V-1508, and also to the single-phase return line through V-1502, V-1503, and V-3102 (Figure 61).

The return flow to the plant is a combination of the flows through the quench valves, through the 20-K lines to valves V-1508, V-1510, V-1411, and through the recoilers and the vapor return line, through V-1421. The combined flows are returned through valve V-1321 to the first stage compressor(s).

Expected cooldown time is 60 h. The status of the system after cooldown to 20 K is "SYSTEM AT 20 K." The 80-K and 20-K thermal shields are kept at their nominal temperature range by nitrogen and helium flows. All helium valves in the string, *i.e.*, cooldown, quench, recoiler level, and lead cooling valves, are closed. No flow is necessary in the coldmass. The helium inventory in the sector is approximately 865 kg at a pressure of 0.3 MPa.

5.3.3.5 Sector Cooldown to 4–5 K and Fill-up

This is the final stage of cooldown, during which the magnet string is cooled to 4–5 K and filled. Before starting this process the helium dewar is filled with liquid delivered from external sources. The refrigerator supplies 4.5-K, 4-bar flow through V-1502 and through the single-phase feed lines. The flow can be supplied directly from the dewar via valve V-1504 (Figure 62), or if a pump is available, through valve V-1515 (Figure 63). As the cooldown wave travels through the string, inventory accumulates behind the wave. As a result, the returning flow rate is much lower than the supply flowrate (4–7% of feed flow). The refrigerator will experience an imbalance in flows and will operate mainly in liquefaction mode. The mass to/from the coldbox is balanced by additional flow from the dewar, which is evaporated in the precooler. The 20-K vapor returning from the tunnel bypasses the heat exchanger (V-3102) and is diverted through V-1507 and returned to the heat exchanger stack via V-1422. If the final cooldown and fill are directly from the dewar, without the plant operating, the flow to the strings is two-phase, which is undesirable. To prevent this situation a pump may be operated.

The flow rates in the 80-K and 20-K shields are kept at their nominal rates. About 200 g/s of 4.5-K, 4-bar helium from the precooler (valve V-1502) is supplied to the single-phase main feed supply line. At 100 g/s per string, the cooldown process takes approximately 12 h.

System status after cooldown to liquid temperatures is "COLDMASS AT 4 K," and the system pressure is 3–4 bar. After cooldown to 4–5 K the recoilers are filled, and their level control loops may be activated. At this point the cold compressor is started, and the pressure in the vapor return lines is lowered to their nominal values. After all the operating parameters have settled to their nominal values, the status of the ring is changed to "STANDBY COLD." About 9700 kg of helium inventory is present in the magnet strings when the cooldown and fill-up processes are completed.

Figure 61. Sector Coldmass Cooldown, 80 K to 20 K.

Figure 63. Sector Fill-up from Dewar Using Pump.

5.3.4 System Warm-up

Warm-up of the system serves three major purposes:

1. Warm-up cycle for the desorption of gas from the beam tube. This process is designed to be performed for the whole sector at a time and not for particular sections. The final temperature may be in the range of 20–50 K.
2. Long-term system storage. There are three different temperatures at which the system can be stored:
 - Coldmass at 20 K. The 20-K and 80-K shield systems are active.
 - Coldmass at 80 K. Only the 80-K nitrogen shield system is active.
 - Coldmass at 300 K. System is empty and clean.
3. Warm-up for maintenance. System is warmed up to 300 K for maintenance or changes.

5.3.4.1 System Emptying and Warm-up to 20 K

Prior to warm-up, the liquid inventory of the magnets has to be transferred to the storage dewars on the surface. System initial status before emptying is "STANDBY COLD." The strings are cold at 4 K, and there is no flow in the coldmass. The 20-K shield and 80-K shield loops are running.

By opening a quench valve in the magnet string and lowering the pressure in the 4-K lines, high-pressure (5–6 bar) 20-K helium is allowed into the magnet coldmass cooling channels. The flow rate is controlled to maintain the pressure supercritical during this procedure. The supercritical 4-K helium is pushed out of the magnet strings, displaced by the 20-K helium gas in both directions: (1) toward the feed spool; and (2) toward the end spool and then back to the feed spool through the 4-K liquid return line (Figure 64). In order to empty the coldmass and the 4-K liquid return lines simultaneously, the 20-K helium is introduced into the coldmass through a quench valve, at approximately two-thirds of the length of the string from the feed spool.

The lower temperature loops in the refrigerator, including the expanders, are activated to process the 4-K gas from the dewar displaced by the 4-K liquid transferred to the dewar. Part of the 4-K gas is used to make up for the 20-K supply; the rest is liquefied and returned to the dewar. For this process, the energy and mass balances in the refrigerator may require additional helium to be drawn from the warm-gas storage tanks. After emptying, this helium is returned to the tanks.

The inventory from the string is transferred to the dewars as long as the enthalpy of helium exiting the strings is below 30 J/g (corresponding to the saturated vapor enthalpy in the dewar). At a flow rate of 100 g/s of 20-K helium for each string, this will take approximately 2–3 h. After this time, the return flow from the string is routed to the coldbox, and the process is continued until the string is warmed up to ~20 K in 4–5 h. About 8000 kg of helium is removed from a sector to the surface dewars during this emptying and warm-up process.

5.3.4.2 System Warm-up to 80 K and to 300 K

For warm-up to 300 K, warm, clean, high-pressure gas from the refrigerator is supplied to the 4-K supply line through the cooldown supply line. Similar to the cooldown process to manage magnet stresses, the supply temperature of the warm-up gas is controlled by mixing warm and 80-K gas.

System initial status is "SYSTEM AT 20 K." Thermal shields operate at nominal temperatures and nominal flow rates. The coldmass is at 20 K and at low pressure (1–2 bar).

Warm, pure, high-pressure gas is supplied through control valve V-1362 and via crossover valve V-1462 into the single-phase main feed line (Figure 65). The surface precooler is bypassed by opening bypass valve V-1508 and closing V-1501 and V-1502. An alternative is to pressurize the warm return header to at least 2 bar in order to supply warm gas; in this case, the cold flow is returned through the 20-K lines via the quench valves (also shown in Figure 65). This allows a parallel warm-up of the shorter lengths of the string, decreasing the warm-up time required. This also "softens" the warm-up rate, thereby reducing the stresses in the magnets during warm-up.

Figure 64. Sector Emptying.

The warm-up process can be stopped at different temperature levels; the temperature level will define the status of the system. For long-time storage of the system at nitrogen temperatures, the 80-K shields are operated at nominal conditions, and the 20-K and 4-K flows can be disconnected.

Excess inventory from the rings is stored on the surface in the gas tanks. The heater in the bypass between the 20-K feed and return lines is used to warm the cold gas from the strings.

Flow resistance limits the flow that can be circulated through the string. The warm-up rate will vary, depending on the routes used for the supply and return flows. The warm-up rate may also be limited by the capacity of the 20-K bypass heater. At 100 g/s per string and with adequate heater capacity, warm-up to 80 K will take approximately 3 days, and warm-up to 300 K about 10 days. Warm-up times can be reduced by using the parallel warm-up method and by using individual heaters for each cell.

5.3.5 Section Repair

The repair of a ring component such as a magnet or spool requires isolation of the section containing the faulty component from the rest of the ring. The flows to the rest of the ring must be rerouted to keep it cold. Removal or repair of a specific component also requires breaking of the vacuum in a half-cell, which is done at room temperature. A section is the smallest part of the ring that can be isolated and warmed up as a unit. HEB sections range from 1104 m to 1628 m.

5.3.5.1 String Emptying

The entire string has to be emptied before maintenance personnel are allowed into the tunnel to perform isolation of the section for repair. This is done by a procedure similar to that described in Section 5.3.4.1.

5.3.5.2 Section Isolation

All the cryogenic lines are depressurized to 1 bar. The cryogenic flows in the neighboring sections are reconfigured to keep the rest of the system cold, and in particular, to keep the nitrogen in the 80-K lines running. Figure 66 shows configurations of the cryogen flows in the rest of the ring.

5.3.5.3 Section Warmup

The warm-up of a single section without warm-up of the remainder of the strings requires external warm helium circulation. There are three options for warm-up of a section:

1. Warm-up using helium from the warm-helium return header (Figure 67). This option requires a blower and heaters. The warm-up rate will be limited by the blower's head production, assuming the heaters have sufficient capacity. Warm gas in the warm return header is compressed by a blower and is supplied into the 20-K line. The quench valves are opened to allow flow into the coldmass. The flow exits through the cooldown valves and is heated before it is returned to the warm return header.
2. Warm-up without a blower, using helium from the 20-K line, requires a helium stream from the refrigeration loop (Figure 68). Some flow from the 20-K loop can be used for this warm-up process. The supply pressure is higher in this case, allowing a higher flow rate—and in turn, a higher warm-up rate—to be achieved. The 20-K flow is heated and delivered through the quench valve into the coldmass. The flow exits through the cooldown valves and is heated before it is sent to the warm return header.
3. Warm-up without a blower can also be accomplished using helium from the pressurized warm return header (Figure 69). Warm gas from the return header is supplied into one end of the section via the cooldown valves. The cold gas exits at the other end of the section through a quench valve into the 20-K line. The process is stopped when the exiting gas temperature is higher than 25–30 K.

HEB

Figure 66. Flow Configuration for Section Repair.

Figure 69. Section Warm-up Using Helium from Pressurized Warm Return Header.

5.3.5.4 Section Cleanup

Part of the 20 K flow is used for cleanup, *i.e.*, to remove contamination after repairs. The same arrangement used in option (2) for warm-up of the section can be used for cleanup. Another option is to supply high-purity helium from portable pressurized gas cylinders.

5.3.5.5 Section Cooldown and Fill-up after Magnet Repair

Cooldown of the section, with the other section already being cold, is accomplished by cooling of the 80-K shield through release of nitrogen into the section. Next, the 20-K shield is cooled by a controlled and moderate 20-K flow. The coldmass is cooled by opening the quench valves and allowing the 20-K into the coldmass, and the warm gas is vented through the cooldown valves to the warm return header (Figure 69). When the temperature of the warm gas drops below a setpoint value, the cooldown valves and the quench valves are closed. A controlled flow rate of single-phase helium feed (4 K, 4 bar) is allowed into the string for further cooldown and fill of the coldmass. For string cooldown to 5 K and fill-up, the same process as defined in Section 5.3.3.5 is used.

5.4 Emergency Operations —Line Failure or Vacuum Break

In the case of a cryogen line failure or loss of insulating vacuum, the 4-K helium flow to the faulty string is stopped, and the string is emptied and depressurized as soon as possible. The section is then warmed up, repaired, and cooled down according to the procedure described in Section 5.3.5. References 7–9 and 19 present analyses of line rupture and cryogen spillage into the tunnel.

6.0 CRYOGENIC CONTROL INSTRUMENTATION

The instrumentation for the HEB ring components is listed in Table 20. Schematics of cryogenic instrumentation for spools SPXA/SPRA, SPRF, SPRI, SPRE, SPRB, and SPRT are shown in Figures 28, 30, 32, 34, 35, and 36, respectively.

Table 20. Cryogenic Instrumentation for the Ring Components.

Types of Spools Number of Spools	SPXA	SPRA	SPRF	SPRE	SPRI	SPRT	SPRB	TOTAL
Quench Valve Actuator	139	139	2	2	4	17	12	315
Quench Valve Position	278	278	4	4	8	34	24	630
Quench Valve Temperature	139	139	2	2	4	17	12	315
Cooldown Valve Actuator	139		2	2	4			147
Cooldown Valve Position	278		4	4	8			294
Cooldown Valve Temperature	139		2	2	4			147
Recooler Valve Actuator		139	2	2	4	17	12	176
Recooler Valve Position		278	4	4	8	34	24	352
Recooler Inlet Temperature		139	2	2	4	17	12	176
Recooler Outlet Temperature		139	2	2	4	17	12	176
Recooler Liquid Level		139	2	2	4	17	12	176
Line 1 Relief Valve Temperature			4	4	8			16
Line 2 Relief Valve Temperature			4	4	8			16
Line 3 Relief Valve Temperature			4	4	8			16
Line 4 Relief Valve Temperature			4	4	8			16
Line 5 Relief Valve Temperature			4	4	8			16
Line 6 Relief Valve Temperature			4	4	8			16
Line 2 Temperature			4	4	8			16
Line 3 Temperature			4	4	8			16
Line 4 Temperature			4	4	8			16
Line 5 Temperature			4	4	8			16
Line 6 Temperature			4	4	8			16
Line 1 Pressure			4	4	8			16
Line 2 Pressure			4	4	8			16
Line 3 Pressure			4	4	8			16
Line 4 Pressure			4	4	8			16
Line 5 Pressure			4	4	8			16
Line 6 Pressure			4	4	8			16
Power Leads Control Valve Actuator			8	8	16			32
Power Leads Control Valve Position			16	16	32			64
Power Leads Temperature			8	8	16			32
CEPL Valve Actuator		278						278
CEPL Valve Position		556						556
CEPL Temperature		278						278
Cooldown Valve Actuator, Lines 2,3,4,5,6			20	20	40			80
Cooldown Valve Position, Lines 2,3,4,5,6			40	40	80			160
Cooldown Valve Temperature, Lines 2,3,4,5,6			20	20	40			80
LN Isolation Valves Actuation					8			8
GN Isolation Valves Actuation					8			8
LN Isolation Valves Position					16			16
GN Isolation Valves Position					16			16
N2 Recooler Control Valve Actuator					4			4
N2 Recooler Control Valve Position					8			8
N2 Recooler Liquid Level					4			4
N2 Recooler Outlet Temperature					4			4
N2 Continuous Recooling Control Valve (Optional)			V	V	V			
4K Injection Control Valve into 20 K (Quench Valve may be used instead)			2	2	4			8
SUMMARY	SPXA	SPRA	SPRF	SPRE	SPRI	SPRT	SPRB	TOTAL
Total number of analog actuators		417	10	10	24	17	12	490
Total number of ON-OFF actuators	278	139	24	24	64	17	12	558
Total number of position switches	556	1112	68	68	176	68	48	2096
Total number of temperature sensors	278	695	80	80	164	51	36	1384
Total number of Pressure sensors			24	24	48			96
Total number of level sensors		139	2	2	8	17	12	180
Total I/O Points for the HEB Ring Cryogenic System								4804

7.0 VALUE ENGINEERING TRADE-OFFS

The primary topics discussed in the "Value Engineering" working groups during August and September 1993 were the following:

- *Is it possible to reduce the number of MLI layers on the 80-K shield?*

The design of the 80-K shield MLI (multi-layer insulation) in the cryostats is based on 64 layers. The cost of the shield and the MLI may be reduced if the insulation is eliminated or the number of layers reduced. However, the resulting increase in the heat leak renders the LN₂ demand too high for the designed distribution system. To handle this demand, an increase in the LN₂ pipe diameter of the cryostats will probably be required. This may in turn require an increase in the external diameter of the cryostats to accommodate the larger pipes. In addition, the 20-K refrigeration load will increase. This load is already large, so that the SRS has to be operated in a special way to support the additional load.

Based on the given data and calculations made by the Magnet Division, it is conceivable to reduce the number of layers to 48. However, the margins for the SRS operation and the limits on the temperature variations in the coldmass make this savings very dangerous.

- *Is it possible to reduce the number of vacuum barriers in the spool pieces?*

The vacuum barrier was removed from the SPXA spools in the HEB. The question was whether it is possible to go a step further and remove vacuum barriers from the SPRA.

The optimization of the distance between the vacuum barriers was done in the Central Design Group (CDG). The work was based on system reliability, maintainability, time to pump-down, and time to detect vacuum problems. Based on the CDG reasoning, the answer to the question was that it is not possible to remove the vacuum barriers from the SPRA in the HEB.

- *Is it possible to replace the SPRI in H30 and H70 by a regular SPRA?*

The design of the SPRI in H30 and H70 is very complicated and costly, requiring a wider tunnel and special transportation and installation procedures. The question was whether it is possible to replace it by a regular SPRA, thereby removing the "isolation" features.

It was suggested that an SPRA could be used with a special arrangement to connect to the nitrogen recooler. Canceling the isolation features will increase the time for pumpdown and leak-check of the beam tube, and the time for the desorption process. During maintenance or magnet replacement, the whole string will have to be warmed up.

- *Is it possible to replace the collider-to-HEB Cryogenic Transfer Line by a direct local supply of nitrogen to the HEB (three trucks a day)?*

Without the helium lines, there is no way through which one refrigeration system (HEB) can assist the other system (the cluster region of the collider).

- *Is it possible to reduce the number of quench valves, from one quench valve per spool to one quench valve every other spool?*

The high dynamic heat load of the HEB will probably require crossflow cooling in the magnets. Helium venting during a quench through magnets with crossflow cooling passages is not well understood and needs further study and experimental verification. The number, size, and frequency of quench valves can be revised, depending on experimental results with half-cell and full-cell string tests.

- *Are bypass lead cooling valves required in every spool?*

The HEB heat budget allocates liquefaction and refrigeration loads for bypass lead cooling in all the SPXA- and SPRA-type spools. Figure 3.2.1.1-2 in the HEB Level 3B Specification¹ shows one bypass lead per cell (either at every SPXA or at every SPRA). Therefore, bypass cooling valves are not required at every spool; as a result, the total liquefaction and refrigeration budget loads can be reduced slightly.

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APPENDIX

DETAILED HEAT LOAD BUDGETS FOR THE HEB

<h1 style="text-align: center;">Appendix</h1> <h2 style="text-align: center;">Detailed Heat Load Budgets for the HEB</h2>						
May 1993: A. Yucel and S. Abramovich						
1) HQM3's replaced by HQM's in the lattice						
2) Updated numbers for N2 distribution loads						
Mar 1994: A. Yucel and S. Abramovich						
1) Updated support and radiant heat loads for connection boxes						
2) Added valve heat leaks for connection boxes						
3) Deleted nominal vs design heat loads - have design only (1 W/m)						
4) Updated bypass elements in short and long straight segments						
5) Updated sector distribution loads						
A. MODEL INPUTS						
1a) Component Arrangement						
Number of Dipoles per Cell		4				
1b) Component Lengths						
Length of Cell		65 m				
Length of Short Straight Section		232 m				
Length of Long Straight Section		390 m				
2a) Dipole Parameters						
Length of Dipole		12.288 m				
Number of Posts in Dipole		5				
Number of Splices in Dipole		7				
2b) Empty Cryostat						
Length of Cryostat EC 6.5		6.5 m				
Number of Posts in Cryostat		2				
Number of Splices in Cryostat		4				
Length of Cryostat EC 2.8		2.8 m				

			Liquif. g/s	4 K Watts	20 K Watts	80 K Watts
3) Quadrupole Parameters						
Length of Quadrupole	1.6	m				
Number of Posts in Quadrupole	2					
Number of Splices in Quadrupole	11					
Length of Quadrupole HQM1	0.902	m				
Length of Quadrupole HQM2	1.173	m				
Length of Quadrupole HQM3	2.258	m				
Length of Quadrupole HQM4	3.347	m				
4) Spool Parameters						
Length of Spool	3.675	m				
Number of Posts in Spool	2					
Number of Splices in Spool	4					
MLI Factor				2	2	2
4) Bypass Feed/End/Isolation Spool Parameters						
Length of Feed/End/Iso. Spool	7.35	m				
Number of Posts in Spool	4					
Number of Splices in Spool	8					
MLI Factor				2	2	2
5a) Special Spool Parameters						
Length of Spool-1m	1					
Length of Spool-2m	2					
Number of Posts in Spool	2					
Number of Splices in Spool	4					
MLI Factor				2	2	2
5b) Bypass Parameters						
Length of Bypass Cryostat	13.171	m				
Number of Supports	3					
Number of Splices	4					
Number of lines in bypass	6					
6) Interconnect Parameters						
Interconnect Length	0.883	m				
Interconnect Heat Leak Allowances				0.21	0.44	3.5

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
7) Beam-Dependent Heat Loads						
Ramping Heat Load per Meter (Nominal)				0.5		
Ramping Heat Load per Meter (Design)				1		
Splice Heat Load per Splice				0.02		
Beam Microwave Heat Load per Meter				0.0023		
Beam Microwave Heat Load per Connection				0.16		
Beam - Gas Heat Load per Meter				0.0086		
8) Component Parameters, General						
Infrared Heat Load per Meter				0.0044	0.185	1.52
Conduction Heat Leak per Post				0.04	0.58	3.8
Beam Position Monitor Heat Load				0.2	0.6	1
9) Component Parameters, Spool						
Number of Support Posts	3					
Vacuum Barrier Heat Load				0.5	4	15
Quench Vent Valve				0.033	5	4
Recooler Feed Valve				0.033	0.288	1.4
Recooler Level Gauge				0.033	0.288	1.4
Beam Tube Sniffer Line				0.033	0.288	1.4
10) Relief Line Heat Loads						
Single Phase Relief Line				0.033	0.288	1.4
Helium Return Relief Line				0.033	0.288	1.4
Gas Return Relief Line				0.033	0.288	1.4
20 K Shield Relief Line					0.3	1.5
80 K Shield Relief Line						2

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
11) Lead Heat Loads						
6.6 kA Lead Pair			0.792	15.84	2	10
CEPL Heat Load			0.06	1.2	1	5
Bypass Lead Pair Heat Load			0.012	0.34	1	5
12) Connection Box Heat Loads						
Single Phase U-Tube				0.884	1.4	7.8
Return Line U-Tube				0.884	1.4	7.8
Gas Return Line U-Tube				1.326	2.28	11.8
20 K U-Tube					4.3	14.8
80 K Valving and U-Tubes						35
Bus Connection				0.1	4	15
Beam Line Transitions				0.066	0.576	2.8
Support and Radiant Heat Loads				0.2	0.5	5
Valve Heat Leaks			0	0.1	0.6	3.6
13) Other Heat Load Allowances per Sector						
Helium Refrigerator - LN2 precooling						30000
Helium Storage			0.8			800
Surface Distribution Box & Interfaces				60	50	400
Helium Pump Box & Interfaces				60		400
Transfer Lines, Bends & Interfaces				120	100	600
Cold Compressor System				150	50	600
Tunnel Distribution Box & Interfaces				100	50	600
Auxiliary End Box & Interfaces				100	50	400
LN2 Pump Box						2400
Utilities						3800
Quench and Cooldown Recovery			3.5			
Performance and Control			1.5	500	800	2000
Total Sector Distribution Loads			5.8	1090	1100	42000
Unallocated			2.4	390	700	0

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
B1. DIPOLE HEAT BUDGET (Including Interconnect)						
1) Static Heat Loads						
Infra-red				0.0541	2.2733	18.6778
Support				0.2000	2.9000	19.0000
Interconnect				0.2100	0.4400	3.5000
Total Static				0.4641	5.6133	41.1778
2) Dynamic Heat Loads						
Ramping				12.2880		
Splices				0.1400		
Beam Microwave Heat Load				0.1883		
Beam - Gas Heat Load				0.1133		
Total Dynamic				12.7295		
Total Dipole				13.1936	5.6133	41.1778

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
B2. EMPTY CRYOSTAT HEAT BUDGET (Including Interconnect)						
1) Static Heat Loads						
Infra-red EC 6.5				0.0286	1.2025	9.8800
Infra-red EC 2.8				0.0123	0.5180	4.2560
Support				0.0800	1.1600	7.6000
Interconnect				0.2100	0.4400	3.5000
Total Static EC 6.5				0.3186	2.8025	20.9800
Total Static EC 2.8				0.3023	2.1180	15.3560
2) Dynamic Heat Loads						
Splices				0.0800		
Beam Microwave Heat Load EC 6.5				0.1750		
Beam - Gas Heat Load EC 6.5				0.0635		
Beam Microwave Heat Load EC 2.8				0.1664		
Beam - Gas Heat Load EC 2.8				0.0317		
Total Dynamic EC 6.5				0.3184		
Total Dynamic EC 2.8				0.2781		
Total Empty Cryostat EC 6.5				0.6370	2.8025	20.9800
Total Empty Cryostat EC 2.8				0.5804	2.1180	15.3560
B3. BYPASS CRYOSTAT HEAT BUDGET (Including Interconnect)						
1) Static Heat Loads						
Infra-red				0.0580	2.4366	20.0199
Support	0.6000			0.0720	1.0440	6.8400
Total Static				0.1300	3.4806	26.8599
2) Dynamic Heat Loads						
Splices				0.0800		
Total Bypass Cryostat				0.2100	3.4806	26.8599

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
C. QUADRUPOLE HEAT BUDGET (Including Interconnect)						
1) Static Heat Loads						
Infra-red				0.0070	0.2960	2.4320
Support				0.0800	1.1600	7.6000
Interconnect				0.2100	0.4400	3.5000
Total Static			0	0.2970	1.8960	13.5320
2) Dynamic Heat Loads						
Ramping				1.6000		
Splices				0.2200		
Beam Microwave Heat Load				0.1637		
Beam - Gas Heat Load				0.0214		
Total Dynamic				2.0050		
Total Quadrupole				2.3021	1.8960	13.5320

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
C1. HQM1 HEAT BUDGET (Including Interconnect)						
Total Static				0.2940	1.7669	12.4710
Total Dynamic				1.2994		
Total HQM1				1.5934	1.7669	12.4710
C2. HQM2 HEAT BUDGET (Including Interconnect)						
Total Static				0.2952	1.8170	12.8830
Total Dynamic				1.5734		
Total HQM2				1.8685	1.8170	12.8830
C3. HQM3 HEAT BUDGET (Including Interconnect)						
Total Static				0.2999	2.0177	14.5322
Total Dynamic				2.6702		
Total HQM3				2.9701	2.0177	14.5322
C4. HQM4 HEAT BUDGET (Including Interconnect)						
Total Static				0.3047	2.2192	16.1874
Total Dynamic				3.7711		
Total HQM4				4.0758	2.2192	16.1874

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
D. SPOOL SPXA HEAT BUDGET (Including Interconnect)						
1) Static Heat Loads						
Infra-red				0.0323	1.3598	11.1720
Support				0.0800	1.1600	7.6000
Vacuum Barrier				0.5000	4.0000	15.0000
Beam Position Monitor Heat Load			0	0.2000	0.6000	1.0000
Beam Tube Sniffer Line				0.0330	0.2880	1.4000
Quench Vent Valve				0.0330	5.0000	4.0000
CEPL			0.0600	1.2000	1.0000	5.0000
Bypass Lead Pair			0.0120	0.3400	1.0000	5.0000
Interconnect				0.2100	0.4400	3.5000
Total Static			0.0720	2.6283	14.8478	53.6720
2) Dynamic Heat Loads						
Splices				0.0800		
Beam Microwave Heat Load				0.1685		
Beam - Gas Heat Load				0.0392		
Total Dynamic				0.2877		
Total Spool SPXA			0.0720	2.9160	14.8478	53.6720
E. SPOOL SPRA HEAT BUDGET (Including Interconnect)						
1) Static Heat Loads						
Total Static Spool SPXA			0.0720	2.6283	14.8478	53.6720
Single Phase Relief Line			0	0.0330	0.2880	1.4000
Recooler Feed Valve			0	0.0330	0.2880	1.4000
Recooler Level Gauge			0	0.0330	0.2880	1.4000
Total Static			0.0720	2.7273	15.7118	57.8720
2) Dynamic Heat Loads						
Total Dynamic Spool SPXA				0.2877		
Total Spool SPRA			0.0720	3.0150	15.7118	57.8720

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
F. SPOOL SPXU (Including Interconnect)						
1) Static Heat Loads						
Infra-red				0.0088	0.3700	3.0400
Support				0.0800	1.1600	7.6000
Quench Vent Valve				0.0330	5.0000	4.0000
Bypass Lead Pair			0.0120	0.3400	1.0000	5.0000
Interconnect				0.2100	0.4400	3.5000
Total Static			0.0120	0.6718	7.9700	23.1400
2) Dynamic Heat Loads						
Splices				0.0800		
Beam Microwave Heat Load				0.1623		
Beam - Gas Heat Load				0.0162		
Total Dynamic				0.2585		
Total Spool SPXU			0.0120	0.9303	7.9700	23.1400
G. SPOOL SPR1 (Including Interconnect)						
1) Static Heat Loads						
Total Static Spool SPXU			0.0120	0.6718	7.9700	23.1400
Single Phase Relief Line			0	0.0330	0.2880	1.4000
Recooler Feed Valve			0	0.0330	0.2880	1.4000
Recooler Level Gauge			0	0.0330	0.2880	1.4000
Total Static			0.0120	0.7708	8.8340	27.3400
1) Dynamic Heat Loads						
Total Dynamic Spool SPXU				0.2585		
Total Spool SPR1			0.0120	1.0293	8.8340	27.3400

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
J1. END BOX Heat Budget						
(END BOX=BPEB+CBEB+Tube Set)						
1) Static Heat Loads						
Valve Heat Leaks		2		0.6000	4.8000	43.2000
Single Phase U-Tube				0.884	1.4	7.8
Return Line U-Tube				0.884	1.4	7.8
Gas Return Line U-Tube				1.326	2.28	11.8
20 K U-Tube					4.3	14.8
80 K Valving and U-Tubes x2						70
Beam Line Transition				0.033	0.288	1.4
Support and Radiant Heat Loads		2		0.4	1	10
Total Static				4.1270	15.4680	166.8000
1) Dynamic Heat Loads						
Splices		4		0.0800		
Total Bypass End Box				4.2070	15.4680	166.8000
J2. T-BOX Heat Budget						
(T-BOX=BPTB+CBTB+Tube Set)						
1) Static Heat Loads.						
Valve Heat Leaks				0.3000	2.4000	21.6000
Single Phase U-Tube				0.884	1.4	7.8
Return Line U-Tube				0.884	1.4	7.8
Gas Return Line U-Tube				1.326	2.28	11.8
20 K U-Tube					4.3	14.8
80 K Valving and U-Tubes x2						70
Support and Radiant Heat Loads		2		0.4	1	10
Total Static				3.7940	12.7800	143.8000
1) Dynamic Heat Loads						
Splices		4		0.0800		
Total T-Box				3.8740	12.7800	143.8000

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
K1. CELL HEAT LOAD						
1) Static Heat Loads						
Dipoles			0	1.856	22.453	164.711
Quadrupole			0	0.594	3.792	27.064
SP-Type Spool			0.072	2.628	14.848	53.672
SPR Type Spool			0.072	2.727	15.712	57.872
Total Static			0.144	7.806	56.805	303.319
2) Dynamic Heat Loads						
Dipoles			0	50.918	0	0
Quadrupole			0	4.010	0	0
SP-Type Spool			0	0.288	0	0
SPR Type Spool			0	0.288	0	0
Total Dynamic			0	55.504	0	0
Total Cell Heat Load			0.144	63.310	56.805	303.319

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
K2. DISPERSION SUPPRESSOR CELL HEAT LOAD						
(A DS cell has 2 dipoles,"3.5/2" quads+4 EC 6.5s(drift space))						
1) Static Heat Loads						
Dipoles			0	0.928	11.227	82.356
Empty Cryostats (for drift spaces)			0	1.274	11.210	83.920
Quadrupole			0	0.520	3.318	23.681
SPXA Spool			0.072	2.628	14.848	53.672
SPRA Spool			0.072	2.727	15.712	57.872
Total Static			0.144	8.078	56.314	301.501
2) Dynamic Heat Loads						
Dipoles			0	25.459	0	0
Empty Cryostats (for drift spaces)			0	1.274	0	0
Quadrupole			0	3.509	0	0
SPXA Spool			0	0.288	0	0
SPRA Spool			0	0.288	0	0
Total Dynamic			0	30.817	0	0
Total Dispersion Suppressor Heat Load				0.144	38.895	56.314
						301.501

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
L. H2O CCW-String HEAT LOAD						
(CCW-String has 28 arc cells + 2* 1/2 SS + LS)						
1) Static Heat Loads						
Arc.Cells			4.03	218.57	1590.53	8492.93
Short Straight Sections						
6 D, 6 Q			0	4.57	45.06	328.26
2 SPXA, 3 SPRA			0.36	13.44	76.83	280.96
11 EC6.5			0	3.50	30.83	230.78
SPRF			1.73	39.63	39.63	242.34
Total- Short Straight Sections			2.09	61.14	192.35	1082.34
West Long Straight Section						
8 D, 7 Q, 8 HQM1, 2 HQM2			0	8.73	75.95	549.68
1 SPXA, 17 SPRA, 9 SPXU			1.40	55.04	353.68	1245.76
6 EC6.5, 7 EC2.8			0	4.03	31.64	233.37
1 SPRI			1.73	39.63	39.63	242.34
44 Bypass Cryostats			0	5.72	153.15	1181.84
2 End Boxes			0	8.25	30.94	333.60
9 T-Boxes			0	34.15	115.02	1294.20
Total- Long Straight Section			3.13	155.55	800.00	5080.79
Total Static			9.25	435.25	2582.88	14656.06
2) Dynamic Heat Loads						
Arc Cells			0	1554.10	0	0
Short Straight Sections						
6 D, 6 Q			0	88.41	0	0
2 SPXA, 3 SPRA			0	1.44	0	0
11 EC6.5			0	3.50	0	0
SPRF			0	0.66	0	0
Total- Short Straight Sections			0	94.00	0	0
West Long Straight Section						
8 D, 7 Q, 8 HQM1, 2 HQM2			0	129.41	0	0
1 SPXA, 17 SPRA, 9 SPXU			0	7.50	0	0
6 EC6.5, 7 EC2.8			0	3.86	0	0
1 SPRI			0	0.66	0	0
44 Bypass Cryostats			0	3.52	0	0
2 End Boxes			0	0.16	0	0
9 T-Boxes			0	0.72	0	0
Total- Long Straight Section			0	145.83	0	0

Total Dynamic			0	1793.93	0	0
Total H2O CCW-String Load			9.25	2229.18	2582.88	14656.06
M. H2O CW-String HEAT LOAD						
(CW-String has 30 cells + 2* 1/2 SS)						
1) Static Heat Loads						
Arc Cells			5.98	271.08	1728.06	9284.04
Short Straight Sections						
10 D, 8 Q, 4 HQM3, 8 HQM4			0	10.65	97.13	707.66
5 SPXA, 11 SPRA, 4 SPXU			1.20	45.83	278.95	997.51
19 EC 6.5, 2 EC 2.8			0	6.66	57.48	429.33
1 SPRF			1.73	39.63	39.63	242.34
36 Bypass Cryostats			0	4.68	125.30	966.96
4 End Boxes			0	16.51	61.87	667.20
4 T-Boxes			0	15.18	51.12	575.20
Total- Short Straight Sections			2.93	139.13	711.48	4586.21
Total Static			8.90	410.21	2439.54	13870.25
2) Dynamic Heat Loads						
Cells			0	1665.47	0	0
Short Straight Sections						
10 D, 8 Q, 4 HQM3, 8 HQM4			0	184.19	0	0
5 SPXA, 11 SPRA, 4 SPXU			0	5.64	0	0
19 EC 6.5, 2 EC 2.8			0	6.61	0	0
1 SPRF			0	0.66	0	0
36 Bypass Cryostats			0	2.88	0	0
4 End Boxes			0	0.32	0	0
4 T-Boxes			0	0.32	0	0
Total- Short Straight Sections			0	200.60	0	0
Total Dynamic			0	1866.08	0	0
Total H2O CW-String Load			8.90	2276.29	2439.54	13870.25

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
N. H2O CCW-String HEAT LOAD						
String Static Heat Load			9.25	435	2583	14656
String Dynamic Heat Load			0	1794	0	0
H2O CCW-String Total Heat Load			9.25	2229	2583	14656
O. H2O CW-String HEAT LOAD						
String Static Heat Load			8.90	410	2440	13870
String Dynamic Heat Load			0	1866	0	0
H2O CW-String Total Heat Load			8.90	2276	2440	13870
P. H2O PLANT HEAT LOAD						
1) Sector String Heat Loads						
Sector Static Heat Load			18.16	845	5022	28526
Sector Dynamic Heat Load			0	3660	0	0
2) Sector Allowances						
Helium Refrigerator - LN2 precooling			0	0	0	30000
Helium Storage			1	0	0	800
Surface Distribution Box & Interfaces			0	60	50	400
Helium Pump Box & Interfaces			0	60	0	400
Transfer Lines, Bends & Interfaces			0	120	100	600
Cold Compressor System			0	150	50	600
Tunnel Distribution Box & Interfaces			0	100	50	600
Auxiliary End Box & Interfaces			0	100	50	400
LN2 Pump Box			0	0	0	2400
Utilities			0	0	0	3800
Quench and Cooldown Recovery			4	0	0	0
Performance and Control			2	500	800	2000
Unallocated			12	0	3878	8474
H2O Plant Total Heat Load						
			36	5595	10000	79000

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
Q. H2O CCW-String HEAT LOAD						
1) String Static Heat Load						
Dipoles (126)			0	58.47	707.27	5188.40
Quadrupoles (69)			0	20.50	130.82	933.71
HQM1 (8)			0	2.35	14.13	99.77
HQM2 (2)			0	0.59	3.63	25.77
SPXA Spools (31)			2.23	81.48	460.28	1663.83
SPRA Spools (48)			3.46	130.91	754.16	2777.86
SPXU Spools (9)			0.11	6.05	71.73	208.26
Empty Cryostats 6.5 m (17)			0	5.42	47.64	356.66
Empty Cryostats 2.8 m (7)			0	2.12	14.83	107.49
SPRI/SPRF/SPRE Spools			3.46	79.25	79.26	484.69
Bypass Cryostats (44)			0	5.72	153.15	1181.84
End Boxes (2)			0	8.25	30.94	333.60
T-Boxes (9)			0	34.15	115.02	1294.20
Total Static			9.25	435	2583	14656
2) String Dynamic Heat Load						
Dipoles (126)			0	1603.92	0	0
Quadrupoles (69)			0	138.35	0	0
HQM1 (8)			0	10.40	0	0
HQM2 (2)			0	3.15	0	0
SPXA Spools (31)			0	8.92	0	0
SPRA Spools (48)			0	13.81	0	0
SPXU Spools (9)			0	2.33	0	0
Empty Cryostats 6.5 m (17)			0	5.41	0	0
Empty Cryostats 2.8 m (7)			0	1.95	0	0
SPRI/SPRF/SPRE Spools			0	1.31	0	0
Bypass Cryostats (44)			0	3.52	0	0
End Boxes (2)			0	0.16	0	0
T-Boxes (9)			0	0.72	0	0
Total Dynamic			0	1793.93	0	0
Total H2O CCW-String Heat Load			9.25	2229	2583	14656

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
R. H2O CW-String HEAT LOAD						
1) String Static Heat Load						
Dipoles (130)			0	60.33	729.73	5353.11
Quadrupoles (68)			0	20.20	128.93	920.18
HQM3 (4)			0	1.20	8.07	58.13
HQM4 (8)			0	2.44	17.75	129.50
SPXA Spools (35)			2.52	91.99	519.67	1878.52
SPRA Spools (40)			2.88	109.09	628.47	2314.88
SPRI/SPRF/SPRE Spools (2)			3.46	79.25	79.26	484.69
SPXU Spools (4)			0.05	2.69	31.88	92.56
Empty Cryostats 6.5 m (19)			0	6.05	53.25	398.62
Empty Cryostats 2.8 m (2)			0	0.60	4.24	30.71
Bypass Cryostats (36)			0	4.68	125.30	966.96
End Boxes (4)			0	16.51	61.87	667.20
T-Boxes (4)			0	15.18	51.12	575.20
Total Static			8.90	410	2440	13870
2) String Dynamic Heat Load						
Dipoles (130)			0	1654.84	0	0
Quadrupoles (68)			0	136.34	0	0
HQM3 (4)			0	10.68	0	0
HQM4 (8)			0	30.17	0	0
SPXA Spools (35)			0	10.07	0	0
SPRA Spools (40)			0	11.51	0	0
SPRI/SPRF/SPRE Spools (2)			0	1.31	0	0
SPXU Spools (4)			0	1.03	0	0
Empty Cryostats 6.5 m (19)			0	6.05	0	0
Empty Cryostats 2.8 m (2)			0	0.56	0	0
Bypass Cryostats (36)			0	2.88	0	0
End Boxes (4)			0	0.32	0	0
T-Boxes (4)			0	0.32	0	0
Total Dynamic			0	1866.08	0	0
Total H2O CW-String Heat Load			8.90	2276	2440	13870

			Liquif.	4 K	20 K	80 K
			g/s	Watts	Watts	Watts
S. H2O PLANT HEAT LOAD						
1) Sector String Heat Loads						
Sector Static Heat Load			18	850	5000	29500
Sector Dynamic Heat Load			0	3660	0	0
2) Sector Allowances						
Helium Refrigerator - LN2 precooling			0	0	0	30000
Helium Storage			1	0	0	800
Surface Distribution Box & Interfaces			0	60	50	400
Helium Pump Box & Interfaces			0	60	0	400
Transfer Lines, Bends & Interfaces			0	120	100	600
Cold Compressor System			0	150	50	600
Tunnel Distribution Box & Interfaces			0	100	50	600
Auxiliary End Box & Interfaces			0	100	50	400
LN2 Pump Box			0	0	0	2400
Utilities			0	0	0	3800
Quench and Cooldown Recovery			4	0	0	0
Performance and Control			2	500	800	2000
Unallocated			12	0	3900	8500
H2O Plant Total Heat Load			36	5600	10000	80000