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and the Status of Their Development***

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CRYOGENIC SYSTEMS FOR THE SSC AND THE STATUS OF THEIR DEVELOPMENT

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INTRODUCTION

The Superconducting Super Collider (SSC) consists of two parallel magnet rings, each 87,120 m in circumference, constructed in a tunnel 25 to 74 m underground. Protons are injected into these rings from the high energy booster (HEB), which contains a separate magnet ring 10,800 m in circumference constructed in a tunnel 14 m above the collider tunnel. Figure 1 is a schematic of the collider and HEB rings. The magnets will be operated at a controlled low temperature in order to maintain the windings in the superconducting state. Therefore the magnet cryostat is designed with a high vacuum insulating chamber, multilayer insulation (MLI), and thermal shields at 84 K and 20 K nominal temperatures. The major portion of the heat load is from thermal radiation and conduction through the supports, and is intercepted and absorbed by the shields.

The cryogenic system for the machine is divided into sectors of nominally equal length: ten for the collider (including both upper and lower rings) and two for the HEB. Each sector has a dedicated cryogenic system (SCS) as well as some level of redundancy from the neighboring SCS. The helium refrigeration plants will be installed at the midpoint of each sector, as shown in Figures 1 and 2. Each cryogenic sector in the collider is divided into four strings, two upper and two lower, about 4000 m long. Each string is subdivided into sections of about 1080 m, the smallest modules that can be isolated for maintenance, or for warmup and cooldown. Each section is subdivided into cells and half cells. The half cell, containing six main magnets (five dipoles and one quadrupole) and a spool piece (a special box for cryogenics, vacuum, electrical, and beam physics measurements and controls), is 90 m long.

The SSC cryogenic system for each sector consists of a sector refrigerator surface system (SRS) and a sector refrigerator tunnel system (SRT). Proposals for the SRS systems¹ are presently in review for vendor selection. In this paper the SRT subsystems requirements and their status will be reviewed.

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Figure 1. Helium refrigeration plants at the SSC, with location of cryogenic plants [□] and sector boundaries [○].

Figure 2. Sector cryogenic system (SCS).

CRYOGENIC TUNNEL SUBSYSTEM

The helium refrigeration plants,^{1,2,3} which provide the 4-K and 20-K refrigeration and the lead cooling flow, will be installed above ground at the midpoint of each sector. Nitrogen⁴ dewars will also be provided at these sites, communicating with the magnet rings for 84-K shield cooling. The sector refrigerator surface systems (SRS), whose capacity requirements are shown in Table 1, are connected to the magnet rings through the sector refrigerator tunnel system (SRT) (Figure 2). The SCS operating conditions are given in Table 2.

The SRT consists of shaft transfer lines (STL), cold compressor box (CCB), tunnel distribution box (TDB), nitrogen pump box (NPB), and other tunnel equipment. For the SRT systems, process flow diagrams were developed for each subsystem to cover all the requirements. In addition, certain mechanical conceptual designs were developed to define the space, interfaces, and installation requirements.

At the boundary between each two sectors an auxiliary valve box will control the flow of cryogenics from one sector to the other and the return flows to the refrigerator. Nitrogen subcoolers will be installed and connected to isolation spools, which are at the end of each section (every 1080 m). These subcoolers are heat exchangers that periodically recool the shield liquid nitrogen flow.

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

Table 1. SCS capacity requirements.

	Sector Heat Load	Plant Capacity
4-K Refrigeration	5400 W	6750 W
4-K Liquefaction	36 g/s	45 g/s
20-K Refrigeration	10,000 W	15,000 W

Table 2. Sector cryogenic system (SCS) operating conditions.

Fig. 2 Ref.	Cryogenic Circuits	T (K)		P (bar)		Flow Rate (g/s)		Size (mm)
		Design	Nom.	Design	Nom.	Design	Nom.	
1	4 K He supply	4	20	4	400	400		90
2	4 K He return	4	20	3.5	400	100		90
3	4 K GHe return	4	10	0.75	400	264		110
4	20 K He supply	14	20	3	200	200		90
5	20 K He return	28	20	2	200	200		110
6	84 K LN ₂	80	20	10	TBD	TBD		90
7	84 K VN ₂	84	10	1.2	TBD	TBD		110
8	4 K He supply	4.5	20	4	400	400		90
9	CCB GHe return	6.1	10	1.2	400	264		110
10	4 K He return	4.3	20	3.5	400	100		90
11	Lead Flow	300	20	1.5	54	36		110

SHAFT TRANSFER LINE (STL)

The shaft transfer line⁵ 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 supply, 20-K return, and one line each for 84-K liquid and vapor nitrogen, all enclosed in a common vacuum jacket.

There are ten shaft transfer lines for the collider and two for the HEB, all installed in the utility shafts at the midpoint of the sector. The total length of each STL depends on the depth of the individual utility shaft as well as the respective locations of the surface distribution box and the cold compressor box in the tunnel. STL will hang vertically on the wall of the utility shaft and have a vacuum pumpout port on each end. The shaft depths are given in Table 3, while Figure 3 shows design details of a transfer line.

The vacuum jacket can be made of 600-mm carbon steel pipe and will be designed to maintain a vacuum of 10^{-5} Pa. An 80-K thermal shield and multilayer insulation will be used to reduce heat leaks into the line. The estimated heat load for the STL is 0.1 W/m for the 4-K lines, 0.33 W/m for the 20-K lines, and 4.0 W/m for the 84-K lines. The STL will be built in standard straight modules 12 m long, with standard and special elbow pieces and special makeup pieces; it will be assembled on site. The estimated weight of a module is 150 kg/m.

COLD COMPRESSOR BOX (CCB)

Each sector requires a cold compressor module (see Figure 4), to be installed in the tunnel near the utility shaft. Twelve modules are needed—ten for the collider and two for the HEB. The cold compressor must follow the various operating modes—design, nominal, and standby—as determined by magnet system demand and refrigerator capacity and availability. Table 4 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 the 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.

HORIZONTAL TRANSFER LINE (HTL)

A horizontal transfer line, which connects the cold compressor box and the tunnel distribution box, differs from the shaft transfer line only in its supports and installation. Whereas the STL will be supported vertically in the shaft, the HTL will be supported horizontally from the tunnel ceiling. The HTL for each sector will be approximately 23 m long and will have a vacuum pumpout port at each end. A total of 12 units will be required for the collider and HEB.

Table 3. Depth of shaft at each sector.

Plant Location	N15	N25	N35	N45	N55	S15	S25	S35	S45	S55	H20	H60
Depth (m)	74	34	58	37	41	66	53	27	30	25	58	53

Figure 3. STL geometry and piping details.

Figure 4. Cold compressor box (CCB).

Table 4. Cold compressor.

Mode of Operation	Inlet		Outlet		Flow
	P (bar)	T (K)	P (bar)	%	
Design	0.75	4.3	1.45	65	330
Nominal	0.75	4.3	1.4	60	264
Standby	0.75	4.3	1.35	55	138

TUNNEL DISTRIBUTION BOX (TDB)

The tunnel distribution box (a nitrogen shielded coldbox) is designed for installation in a niche behind the feed spool, in the outer part of the ring. It shall be vacuum-jacketed (10^{-5} Pa) and connected to the cold compressor box through the horizontal transfer line. The TDB itself has four short vacuum-jacketed transfer lines, each containing six pipes, feeding cryogenics to four magnet strings through the feed spool pieces. Figure 5 is a flow diagram for the TDB. Ten TDBs will be required for the collider. Since the HEB has only two strings, it requires only two short transfer lines on each of its two TDBs.

Figure 5. Tunnel distribution box (TDB).

NITROGEN PUMP BOX (NPB)

Approximately 5000 g/s of liquid nitrogen is required for normal operation of the collider and the HEB. The liquid nitrogen will be imported to the SSC 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 systems 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, 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, for the helium refrigerators, and for backup. The pumps will be configured for parallel operation and for interchangeable application.

The subcooler in the nitrogen pump box will be designed to support flow rates in each of two streams up to 2000 g/s, with heat loads up to 6000 W per stream. The box will be an independent vacuum unit (10^{-5} Pa) and will have ports for pumping and monitoring instrumentation. Figure 6 is the flow diagram for the nitrogen pump box.

NITROGEN DUMP TANKS (NDT)

Two uninsulated nitrogen dump tanks will be installed in the niches near the feed spools, and two near the end spools of the sectors. These tanks will be used for emergency venting and may be used during cooldown and warmup. The capacity of the two tanks, 22,000 L (5800 gal), is equal to the total nitrogen inventory in two parallel strings (half a sector). The liquid nitrogen dumped into these tanks will vaporize and will be vented to the atmosphere through a pipe routed to the surface, as shown in Figure 6.

NITROGEN SUBCOOLER BOX (NSB)

To limit the temperature changes of the 84-K shield, the liquid nitrogen must periodically be recooled. The expected heat load of the 84-K system is around 3 kW/km per string, and the maximum temperature of the liquid nitrogen should not exceed 89 K. To cover the whole range of LN_2 flows, including the smallest expected flow rates, the subcoolers will be located near the isolation spools (SPRI). The isolation spools are located every 1080 m, and each has two cryostats connected to one another by six U-tubes, for the six streams in each magnet ring. Thus it seems reasonable to connect the LN_2 subcoolers through these U-tubes. Each two subcoolers (top and bottom) will be incorporated in a single vessel but will have separate streams and controls. A total of 70 nitrogen subcooler boxes will be required for the collider and four for the HEB. Figure 7 is a flow diagram for the nitrogen subcoolers.

AUXILIARY END BOX (AEB)

A set of valves, connecting the six cryogenic lines of neighboring sectors, is required for the nitrogen flows across the sector boundaries during normal operation and for the helium flows when single-phase helium and/or 20-K helium must be transferred from one sector to the other ("assist" mode³). The valve box may be designed as a separate box or may incorporate the nitrogen subcoolers. It will be connected to the center of the end spool, as shown in Figure 8.

Figure 6. Nitrogen pump box (NPB).

Figure 7. Nitrogen subcooler box (NSB).

Figure 8. Auxiliary end box (AEB).

CRYOGENIC BYPASS TRANSFER LINES (CBTL)

In several parts of the collider rings and HEB, the beam tubes pass through warm equipment (magnets, scrapers, injection transfer lines, RF cavities, detectors, etc.). Cryogenic bypass transfer lines will be installed to bridge these regions, and high-current superconducting buses must be routed through the 4-K helium in these transfer lines. A total of 4100 m of bypass lines, consisting of 12 cryogenic lines, will be installed in the collider; 1300 m of bypass lines, consisting of 6 cryogenic lines, will be installed in the HEB. The CBTLs will be designed in standard 15-m modules, with end boxes (BPEB) where the connections to the magnet strings are made, and T-boxes (BPTB) where "T" connections are needed to feed isolated cryostats. The end boxes will contain cryogenic measurement devices, relief and cooldown valves, and vacuum instrumentation. Every 90 m of the transfer line, a box with vacuum barrier, vacuum pumpout ports, and vacuum instrumentation is required. Provision must be made for bus expansion and contraction during cooldown and warmup. Figure 9 is the flow diagram for the BPEB and BPTB.

Figure 9. The BPEB and the BPTB.

INSTRUMENTATION AND CONTROLS

Instrumentation and process controls are part of the various cryogenic equipment such as spool pieces, bypass line end boxes, and other boxes described in the previous paragraphs. Signal conditioners, transmitters, and controllers will be installed in the underground niches.

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