Chapter 11

Cryogenic Systems

11.1 Introduction

In order to apply bulk refrigeration to accelerator components, the cooling requirements for each device need careful consideration. The specification and application of bulk refrigeration will naturally follow a thorough investigation and careful engineering of cooled components. It is this study that sets the stage for making the connection between the cooling requirements and the refrigeration system cooling arrangement and hardware. For our case, the cooled devices are rf cavities, superconducting magnets, and hydrogen absorbers, all of which are well characterized in terms of heat loads.

11.2 Cooled Components

The Neutrino Factory uses cryogenic cooling in all of its major sections. A general listing of the cryogenic cooling needs are:

- The proton driver, which has a superconducting linac (SCL) made of three sections, each with its own energy range and cavity cryostat arrangement, and all operating at 2 K.
- The target station and pion capture system, which utilize 1.9 K and 4.4 K refrigeration for the superconducting capture solenoids.
- The decay channel, which has superconducting magnets operating at 4.4 K.
- The phase rotation section, which uses superconducting solenoids that operate at 4.4 K.

- The mini-cooling section, which has solenoids operating at 4.4 K and two-phase hydrogen absorbers operating at 16-19 K.
- The bunching and cooling channel, which has superconducting solenoids operating at 4.4 K and 2.5 K, as well as liquid-hydrogen absorbers operating at 16-19 K.
- The linear accelerator section, which has superconducting rf cavities operating at 2.5 K and solenoids operating at 4.4 K.
- The recirculating linear accelerator, which again has rf cavities operating at 2.5 K and superconducting magnets operating at 4.4 K.
- The storage ring, which has superconducting dipoles and quadrupoles operating at 4.4 K.

All the superconducting magnets and superconducting rf cavities also require cooling in the 5-8 K and 50-80 K range for shields and current leads. Cryogenic cooling, regardless of temperature, is accomplished via helium refrigeration.

Large helium refrigerators are envisioned here, because they naturally provide all temperature ranges required, and typically provide a higher Carnot efficiency than do smaller units. Larger refrigerators, typically with turbine expanders, also offer enhanced cooling capacity at higher temperatures, as well as options to improve the cool-down and liquefaction processes with the addition of liquid nitrogen. The requirements of superconducting magnets, absorbers, and rf cavities will define the interface between refrigeration and cooled devices.

In the muon cooling channel and the phase rotation channel, a 16 K stream cools the magnet shields and leads as well as the liquid-hydrogen absorbers. Figure 11.1 shows the cooling circuit to a typical coupling ("B") coil in the muon cooling channel. The same type of flow circuit can be applied to the solenoids in the phase rotation section. The focusing ("A") coils in the cooling channel have liquid-hydrogen absorbers within them. The cryostat for the liquid-hydrogen absorber is a part of the magnet cryostat. The 2.75-m-long cell focusing magnets operate at 4.4 K, whereas helium delivered to the hydrogen absorber enters at about 16 K and leaves at about 18 K. Helium entering the absorber heat exchanger must remove about 330 W of heat from the liquid-hydrogen absorber when the full intensity muon beam is present. When there is no beam, the heat into the 16 K helium flow circuit is reduced to about 55 W. Figure 11.2 shows a helium flow circuit for the focusing coil and liquid-hydrogen absorber in a 2.75 m cooling cell. As seen in both Figs. 11.1 and 11.2, the shields and leads are cooled from the 16 K helium circuit. Shield and lead gas exits the cryostat at 300 K. The corresponding 16 K cooling

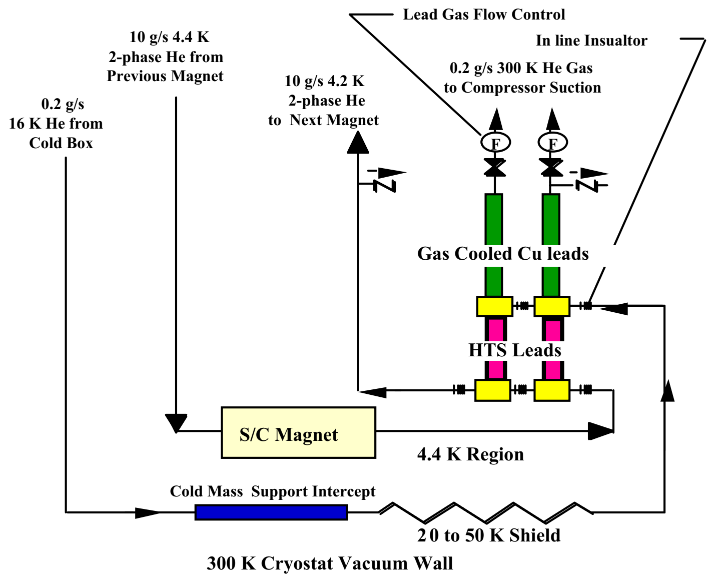

Figure 11.1: The magnet helium cooling circuit for a typical coupling ("B") coil in the cooling section.

requirement for the 1.65 m cell hydrogen-absorbers are 150 W with the muon beam on, and 40 W with the beam off.

The focusing coils in the 1.65-m cooling cell have a peak induction in the winding of 8.5 T. In order for these coils to be made from Nb-Ti, they must operate at a reduced temperature (between 2.5 and 3.0 K). The heat load into the ("A") coils comes from the cold-mass supports and from thermal radiation from the shield; there is almost no heating due to muon decay or AC losses in the superconductor. By using the 4.4 K stream to intercept heat from the cold-mass supports, shield, and leads, the heat leak into the focusing coil can be reduced from 1.8 W to about 0.3 W.

A low heat load at 2.5 K can be removed by using a small 2 K cooling circuit that operates off of the 4.4 K refrigeration circuit. The cooling circuit consists of a heat exchanger that takes liquid helium from the two-phase flow circuit. After passing through the high-pressure side of the heat exchanger, the liquid helium is throttled through an expansion valve down to a pressure of about 40 ton. The helium is now two-phase helium at 2.2 K, with evaporation cooling of the load. The low-pressure gas phase passes through the low-pressure side of the heat exchanger and is finally returned to the refrigerator compressor at 300 K. To generate 0.3 W of cooling at 2.2 to 2.5 K, a helium flow rate of

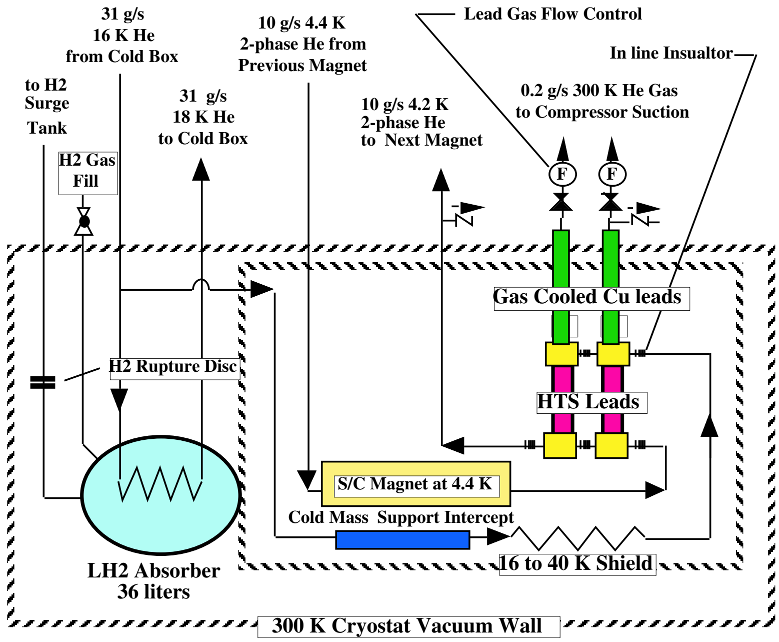

Figure 11.2: The magnet helium cooling circuit for a typical focusing ("A") coil and the liquid-hydrogen absorber in the 2.75-m cooling cell.

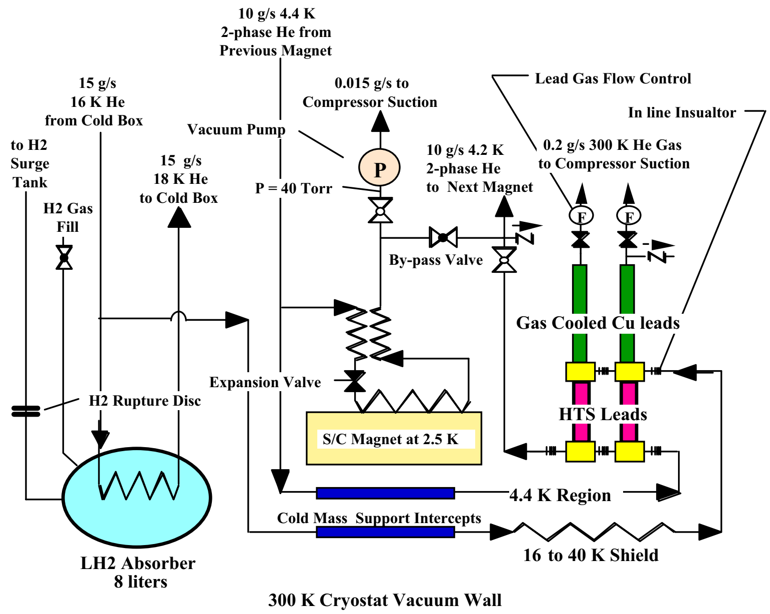

Figure 11.3: A helium cooling circuit for the focusing coils and the liquid-hydrogen absorber in the 1.65-m cooling cell.

0.015 g/s is needed. Since this helium is returned to the refrigerator warm, it is equivalent to helium liquefaction. The liquefaction of 0.015 g/s of helium corresponds to about 1.5 W of refrigeration at 4.4 K. Figure 11.3 shows the helium cooling circuit for a 1.65-m cooling cell ("A") coil and its hydrogen absorber.

11.3 Component Loads

The estimated refrigeration requirements for each cooled device, including the primary static (ambient) and dynamic (beam heating) higher temperature secondary or shield loads, and anticipated cooling arrangement (thermodynamic state) have been considered for the entire accelerator. To ease the evaluation of refrigeration component requirements, the given loads at various state points are all expressed as an equivalent load at 4.5 K. This approach gives a better feel for the refrigeration equipment, and hence a means of comparison with other installations in terms of size, capital cost, and operational demands. Considerations for reliability, helium plant economics (including standard refrigeration availability), installation costs, operation costs and difficulty, are all folded into specifying refrigerators, and in the end will define their sizes and number.

For each group of accelerator components, (see Fig. 11.4 for the approximate location of each group), Table 11.1 shows the integrated primary heat load and thermodynamic state, the secondary heat load and state, and the equivalent loads normalized to 4.5 K. The table follows the accelerator layout, starting at the source and working toward the muon storage ring. The equivalent load at 4.5 K is estimated by multiplying the primary load by the ratio of ideal work at the primary load condition to the equivalent ideal work at 4.5 K. The ideal work is found from Carnot's formula, $\frac{(T_a-2.5)}{2.5}/\frac{(T_a-4.5)}{4.5} \approx 1.8$. for the 2.5 K condition. The temperature T_a is taken as 300 K. The loads summarized in Table 11.2, are in terms of base-load at 4.5 K equivalent, and base-load-equivalent with 30% contingency added. The percentage of total equivalent load at 4.5 K for the primary and/or the secondary load is also shown to give an understanding of the areas of refrigeration concentration, and give a feeling for the relative size requirements.

The last two columns, equivalent primary and equivalent secondary loads, from Table 11.2, are combined to give a summary of the total 4.5 K equivalent loads and equivalent 4.5 K loads with 30% contingency. These values are shown in Table 11.3. It is from this table that a preliminary refrigerator sizing has been made.

11.4 Refrigeration Selection

From Table 11.3 and the accelerator layout an assessment of the number and size of refrigerators, and possible locations is possible. This is reflected in Fig. 11.4. Based upon our understanding of large refrigeration systems applied to accelerators, the choice for this application is to use a few large 4.5 K refrigerators. The low temperature (< 4.5 K) areas are covered using low temperature cold boxes, with cold pumps, tied into the local 4.5 K refrigerator. This design approach minimizes the distance between the load and the cooling system that requires sub-cooling and sub-atmospheric cold pumps. The benefit is a linear reduction of large diameter pumping lines required for this application. Large diameter vacuum insulated transfer lines are very expensive, so minimizing here is prudent. Table 11.3 gives a feeling for the location of these sub-cooling cold boxes, and also suggests ways to isolate and/or group component loads with proximity and capacity considered. A way of coalescing loads by location is shown in Table 11.4.

With reference to Table 11.4, inclusive of contingency, area specific loads at locations ("A"), ("B"), and ("C") could be divided into two 4.5 K refrigerators, for each location, of the approximate capacity of the machines in operation at the Relativistic Heavy Ion Collider at BNL [1], [2], those previously used for the LEP Electron–Positron Collider at CERN [3], ot the new refrigerators under construction for LHC project [4], [5], [6]. For

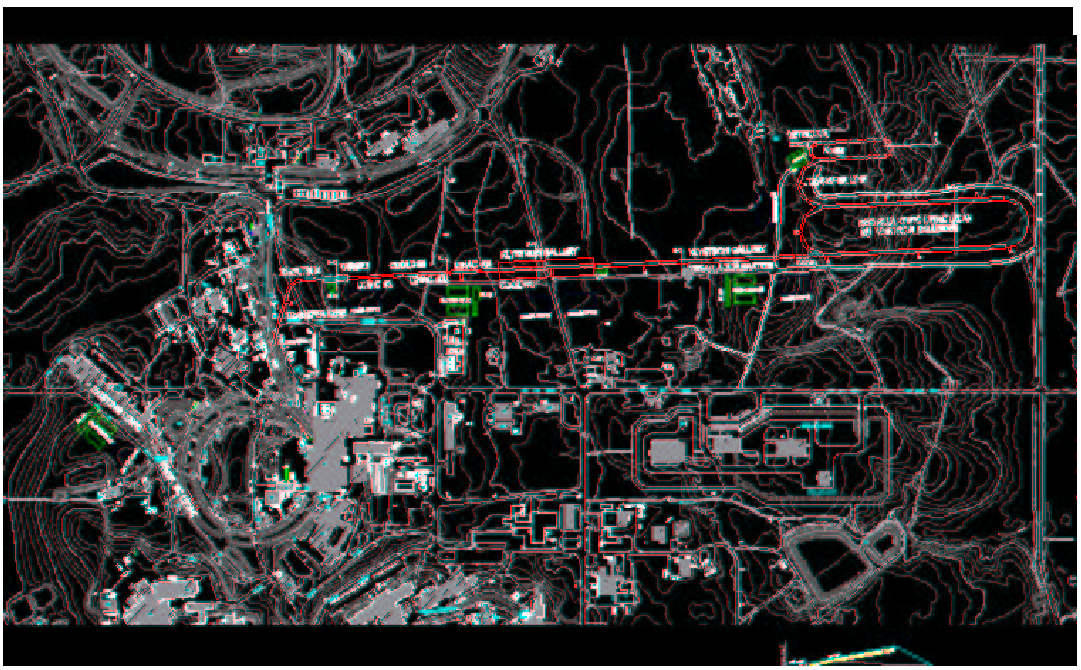

Figure 11.4: Site layout.

purposes of system design here, the 18 kW machines under construction for the LHC are used. Systems of similar size are encountered also in operation at CEBAF (Jefferson Laboratory) [7]. The feasibility of installing refrigerators of the sizes indicated above has certainly been demonstrated at many places.

Integrating local accelerator heat loads into one or more large refrigerators is cost effective in terms of initial capital investment, because it eliminates much of the duplication associated with building many smaller capacity refrigerators. Installation and operation follow the same philosophy. To support the accelerator loads other than 4.5 K, the refrigerators will incorporate process supply and return passes to meet the higher temperature requirements of items such as the shields and absorbers. These secondary loads, shown in Table 11.1, are typical and would be specified as part of a refrigerator procurement. In essence, each refrigerator will supply the 4.5 K for direct application and all higher temperature needs. Also, each refrigerator will provide the necessary refrigeration for the lower temperature cold boxes. Table 11.2 summarizes the actual loads at operating temperatures below 4.5 K.

To produce temperatures below the temperature range of the 4.5 K refrigerators, stand-alone cold boxes, containing at least one heat exchanger and a series of cold compressors are used. The production of 1.9 and 2.5 K cooling, requires pumping on saturated liquid helium to a pressure of 16 or 100 mbar, respectively. The pumping scheme is usually optimized when located as close as possible to the cooled device, so that transfer line hydraulic losses are minimized. This approach also minimizes cost, because low-pressure process pipes, connecting the pumps to accelerator components, are typically much larger diameter (possibly a factor of 4) and therefore more expensive to build than the transfer lines that connect the refrigerator to the low-temperature cold boxes. The actual cold pumps, located within the local cold box, can achieve the desired pressure with a series arrangement, usually 4 or 5 stages being required, or some pumping can be accomplished at room temperature with warm compressors, which reduces the number of cold stages to 3.

11.5 Capital Cost, Installation, and Operation

11.5.1 Capital Cost

The components that drive the capital cost of large cryogenic refrigeration systems, in descending order of relative cost, are:

- the 4.5 K refrigeration and associated warm compressor system, reduced temperature cold boxes and cold compressors

- transfer piping
- process distribution control or valve boxes
- cold and warm helium recovery
- storage volumes and controls.

Building and utility requirements are considered elsewhere (see Chapter 12); here we consider the components associated with refrigeration to the ends of each interface to each cooled device. The component installation and interface costs are specific to each cooled item. From experience with the construction of RHIC, the cost for installation materials and labor, in terms of percentage of capital cost, in descending order, comes from: transfer piping, refrigeration, valve boxes, reduced temperature cold boxes, controls, and helium recovery/storage.

Estimates for cryogenic transfer piping length are based upon the length of the particular device, which were considered as a unit (see Table 11.4) and integrated into one 4.5 K refrigeration plant. In the case of the recirculating linac the perimeter is used, and for the storage ring, with its simpler cooling requirement, the end-to-end length is chosen. A small contingency length is added to these values to allow for connection to the refrigerator (and cold boxes if they are needed).

11.6 Operational Issues

11.6.1 Power, Operations Labor, Maintenance

The operating cost, mainly electrical power, is tied directly to the cycle efficiency. This subject has been addressed in detail for the 18 kW machines at CERN [5], [6] with the present efficiency at about 30% Carnot, yielding a figure of merit (W_{in}/ W_{ref}, 4.5 K) of 250. For our case, the refrigeration with full contingency, 105 kW, corresponds to $\approx$ 26 MW of electrical power. Under normal operating conditions, estimated at 81 kW, the electrical power required is 20 MW.

The labor required to operate a facility of this nature could be derived from the models developed and used at RHIC (BNL), CEBAF (Jefferson Laboratory), or LEP (CERN). For this part of the study, the RHIC facility is used as the model and the operation of LEP is referenced. Information gathered from these operating facilities is used to project the needs for the present study. The same approach is used for maintenance of refrigeration systems. The operation of the four 18 kW plants at LEP involves a group of 37 people, the direct operation and maintenance of the refrigerators is accomplished by

15 persons. Operation of cryogenic systems at BNL includes, RHIC, with its refrigerator and warm compressors, instrumentation and controls, and ring process equipment, g–2, and experimental programs that require cryogenics. The manpower dedicated to the operation of the RHIC refrigerator directly, is on the average higher than at LEP.

11.6.2 Cryogenic Safety

It is of prime importance to consider safety as a criterion when providing refrigeration of this magnitude within the confinement of building structures. Careful attention must be paid to providing an effective means of access and egress for this facility, with its long linear dimensions, because of the possibility of an inadvertent release of cryogen at a high volumetric flow rate under certain fault scenarios. The installation and testing experience gained at RHIC, with reference to work accomplished at the SSC, FNAL, and CEBAF, has shown the prudent approach revolves around good cryogenic component design, governed by conformance to ASME pressure vessel code requirements and strict attention to the minimization of "ODH" (Oxygen Deficiency Hazard) risks. This would be accomplished by designing building ventilation systems to ensure the safest ODH class. These ODH classes range from 0 to 4, and in our case class A0 is selected.

Table 11.1: Devices and heat loads.

Primary Temperature/ State/ Primary Load at State	Cryogenic Secondary (Shield) Load/ State	Approximate Equivalent Primary Load at 4.5 K/ % Total Primary Load Equivalent	Approximate Equivalent Secondary Load at 4.5 K/ % Total Secondary Load Equivalent	
SC Linac rf Cavities / 100 m				
2.5 K/ 2 Phase/ 7.1 kW	8.3 kW/ (5–8 K) 87 kW/ (40–60 K)	12.8 kW/ 21%	8 kW (5–8 K) 8.7 kW (40–60K)/49.7%	
Matching Solenoids (Capture) / 10 m				
1.9 K/ 2 Phase/6.3 kW	0.82 kW/ (30–300)	14.8 kW/ 24%	0.3 kW/0.9%	beam loading
IL1 / 110 m				
4.4 K/ 2 Phase/ 0.55 kW	0.59 kW/ (40–60 K)	0.55 kW/ 0.9%	0.06 kW/ 0 .18%	4.5 K load = 5 W/m
Minicooling / 5 m				
16 K/ 2 Phase/ 5.5 kW		1.5 kW/ 2.4%		
IL2 and IL3 / 190 m				
4.4 K/ 2 Phase/ 0.09 kW	1.0 kW/ (40–60 K)	0.09 kW/ 0.15%	0.1 kW/ 0.3%	4.5 K load = 0.47 W/m
Matching and Bunching Solenoids / 50 m				
4.4 K/ 2 Phase/ 0.27 kW	3.0 kW (16–40 K)	0.27 kW/ 0.44%	0.8 kW/ 2.4%	
Cooling/ 100 m				
16 K/ 2 Phase/ 10.6 kW		2.9 kW/ 4.7%		
Acceleration Linac (11 short, 16 intermediate, 19 long cells) / 250 m				
2.5 K/ 2 Phase/ 1.86 kW	2.2 kW (5–8 K) 22 kW (40–60 K)	3.37 kW/ 5.5%	2.0 kW (5–8 K) 2.2 kW (40–60 K)/ 12.5 %	
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Primary Temperature/ State/ Primary Load at State	Cryogenic Secondary (Shield) Load/ State	Approximate Equivalent Primary Load at 4.5 K/ % Total Primary Load Equivalent	Approximate Equivalent Secondary Load at 4.5 K/ % Total Secondary Load Equivalent	
Recirculating Linac (48 long cells) / 300 m				
2.5 K/ 2 Phase/ 4.7 kW	5.57 kW (5–8 K) 55.7 kW (40–60 K)	8.5 kW/ 13.8%	5 kW (5–8 K) 5.6 kW (40–60K)/ 31.5 %	
Dipole/ Quadrupole Magnets, for Recirculating Linac				
4.4 K/ 2 Phase/ 0.47 kW	6.0 kW/ (40–60 K)	0.47 kW/ 0.76%	0.6 kW/ 1.8%	
Storage ring arcs (53 m $\times 2$ inclined)				
4.4 K/ supercritical/ 1.0 kW (static) + 1.0 kW (dynamic)	2.0 kW/ (40–60 K)	2.0 kW (static & dynamic)/ 3.2%	0.2 kW/ 0.6%	dynamic beam loading

Table 11.2: Load summary.

Total	Primary	Secondary	Primary Equivalent	Secondary Equivalent
Total (2.5 K, 4.4 K, 16 K without contingency)	13.66 kW (2.5 K) 3.38 kW (4.4 K) 16.1 kW (16 K)			
Total (5–8 K, 16–40 K, 40–60 K without contingency)		16.1 kW (5–8 K) 3.0 kW (16–40 K) 124 kW (40–60 k)		
Total equivalent (4.5 K without contingency)			47.4 kW	33.6 kW
Total equivalent (4.5 K with 30% contingency)			61.6 kW	43.7 kW

Table 11.3: Load concentrations and percentages.

Cooled Device	% Total and Equivalent 4.5 K Load in kW (Primary Load)	% Total and Equivalent 4.5 K Load in kW (Secondary Load)	Total Equivalent 4.5 K Refrigeration, Primary plus Secondary in kW/ Total with 30% Contingency in kW
SC linac rf cavities	12.8 kW/ 21%	16.7/ 49.7%	29.5/ 38.4
Matching solenoids (capture) IL1 (110 m)	14.8 kW/ 24% 0.55 kW/ 0.9%	0.3 kW/0.9% 0.06 kW/ 0.18%	15.1/ 19.6 0.61/ 0.8
Minicooling IL2 and IL3 (190 m)	1.5 kW/ 2.4% 0.09 kW/ 0.15%	 0.1 kW/ 0.3%	1.5/ 1.95 0.2/ 0.26
Matching and bunching solenoids	0.27 kW/ 0.44%	0.8 kW/ 2.4%	1.1/ 1.4
Cooling	2.9 kW/ 4.7%		2.9/ 3.8
Acceleration linac (11 short, 16 intermediate, 19 long cells)	3.37 kW/ 5.5%	4.2 kW/ 12.5%	7.7/ 10
Recirculating linac (48 long cells)	8.5 kW/ 13.8%	10.6 kW/ 31.5%	19.1/ 24.8
Dipole/ quadrupole magnets, for recirculating linac	0.47 kW/ 0.76%	0.6 kW/ 1.8%	1.1/ 1.4
Storage ring arcs (53 m x 2 inclined)	2.0 kW/ 3.2%	0.2 kW/ 0.6%	2.2/ 2.9
Total Load	47.4	33.6	81/ 105.3

Table 11.4: Load concentrations grouped by area, with 30% contingency.

A- SC linac rf cavities (kW)	38.4
B- Items 2–7 inclusive, from Table 11.3 (kW)	27.8
C- Acceleration and recirculating linacs (kW)	34.8
D- Storage ring (kW)	3.0

11.6. Operational Issues

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