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AHF MAGNETIC LENS CRYOSYSTEMS

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ABSTRACT

The Advanced Hydrotest Facility (AHF), a proton radiography and tomography facility, is under study at the Los Alamos National Laboratory (LANL). 800-MeV protons from the existing LANSCE linear accelerator are to be accelerated to 50-GeV and the resulting beam split twelve fold during transport through a complex multi-path beam transport and lens system to illuminate a study object along multiple directions. The object-scattered protons are imaged for analysis by a system of large-bore magnetic lenses. Design trade studies have compared normal and superconducting (SC) magnets for the transport and lens systems as well as many other tradeoffs in systems configuration. The development of the helium refrigerator/liquefier size and location, and distribution system for the AHF large-bore (20 and 50 cm diameter) pool-boiling, SC magnetic lens system is described. The magnetic-lens-option cryoplant (13-kW range at 4.43 K) and distribution system are site positioned and sized, and the system, facility and utility costs are estimated and compared to alternatives.

INTRODUCTION

The Advanced Hydrotest Facility (AHF), a significant element of the Stockpile Stewardship Program, will use proton radiography [1] to evaluate otherwise undetectable structure of dynamic events within thick dense objects. The construction and implementation of this dedicated facility will extend the single-axis feasibility-demonstration work done at LANL (800-MeV) and Brookhaven National Laboratory (25-GeV). The AHF characteristics include capability of high-resolution tomography, higher-energy and higher-intensity proton beams (50 GeV), along with high-resolution material identification.

A 3-GeV booster and a 50-GeV synchrotron would accelerate the LANSCE 800-MeV proton beam to 50-GeV. Alternatively, a site-independent linac may be used to inject the booster. The beam is split and transported through a complex multi-path beam-transport and lens system to illuminate a study object along 12 axes [2]. The object-scattered protons are then imaged by a system of large-bore magnetic lenses [3] for analysis.

Superconducting (SC) magnet cryosystem options have been developed for the AHF system shown in FIG 1. The magnet cooling required divides the AHF system into two areas: the lens SC magnets cooled by pool-boiling helium and the beam-transport lattice SC magnets cooled by a flow of supercritical helium. Cryosystems for the later are addressed in reference [4]. This paper presents the development of the cryogenic systems for the large-bore SC-lens option that is part of the project baseline. Provided are recommendations for the helium-refrigerator/liquefier size, its site position, and the distribution system. Additionally, estimates are provided for system costs.

THE LENS SYSTEM

The magnetic lens system contains 12 lens beam-lines arranged to illuminate the study object. There are two types of lens lines: four large-bore and eight small-bore lens lines. The lens beam-line types are constructed of the same functional elements, as shown in FIG

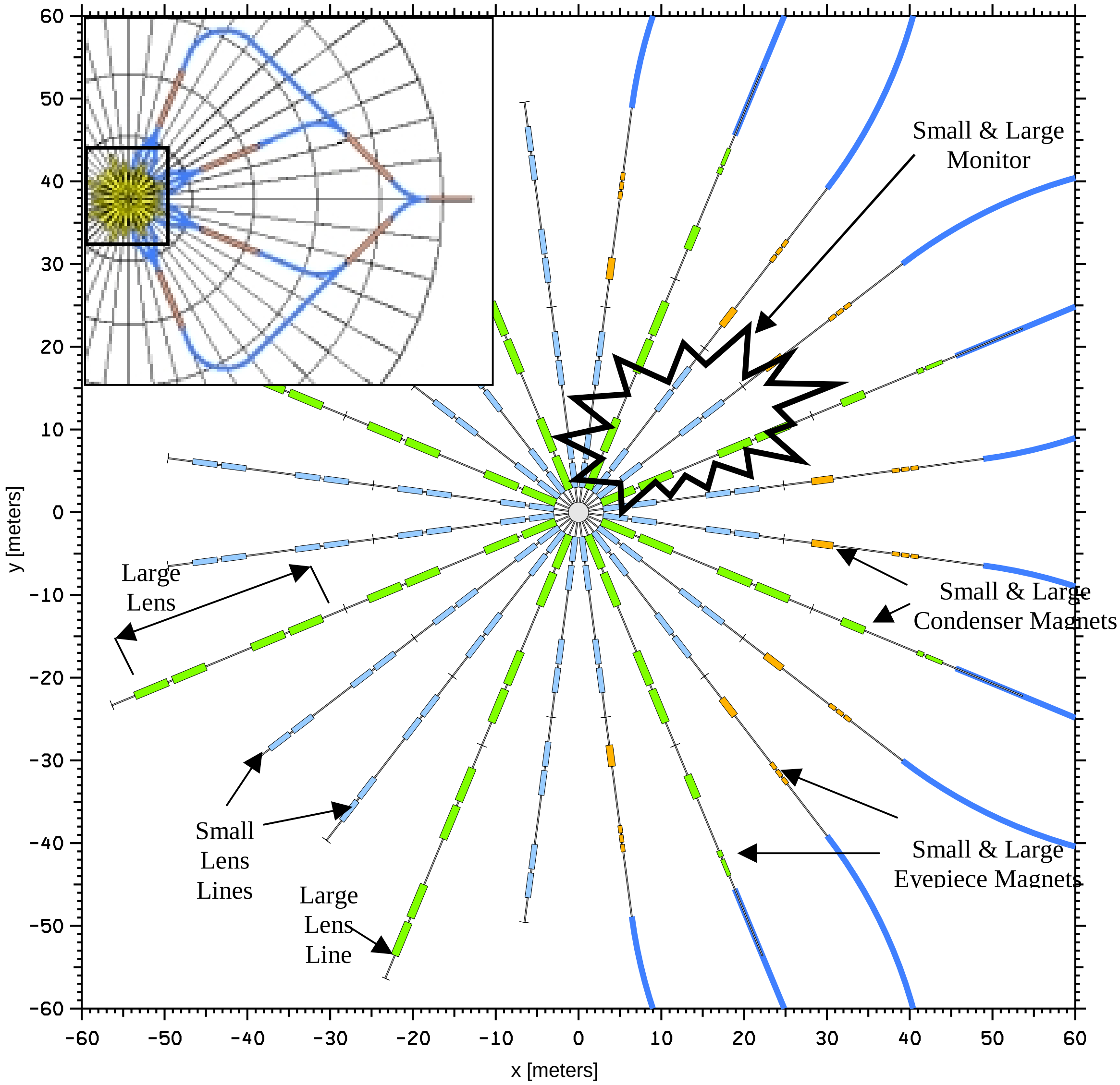

FIGURE 1. The lens system with monitor lenses. In a system without monitor lenses, the condenser and eyepiece magnets would be moved closer to the object. The inserted box shows the lens-system position with respect to the beam-transport lattice.

TABLE 1. Lens Magnets' Cryogenic Parameters

	Small Lens Condenser Magnet	Small Lens Magnet	Large Lens Condenser Magnet	Large Lens Magnet
Ambient Pressure @ LANL (atm)	0.8	0.8	0.8	0.8
Length (m)	2.52	2.90	2.79	4.12
Bore (m)	0.203	0.229	0.483	0.483
Number with (without) Monitor Lenses	8	96 (64)	4	48 (32)
Primary Supply System				
Type of Cooling	Pool Boiling	Pool Boiling	Pool Boiling	Pool Boiling
Nominal Operating Temperature (K)	4.43	4.43	4.43	4.43
Nominal Operating Pressure (atm)	1.125	1.125	1.125	1.125
Heat Load – Calculated (Used) (W)	7.49 (10)	9.71 (10)	19.78 (20)	29.13 (30)
Operating Current (A)	7800	7800	7800	7800
Liquefaction Load (Power Leads)				
Lead Type	Vapor Cooled	Vapor Cooled	Vapor Cooled	Vapor Cooled
Massflow (lead pair) (g/s)	0.87	0.87	0.87	0.87
Inlet Temperature (K)	4.43	4.43	4.43	4.43
Outlet Temperature (K)	~ 300	~ 300	~ 300	~ 300
Inlet Pressure (atm)	1.125	1.125	1.125	1.125
Outlet Pressure (atm)	0.85	0.85	0.85	0.85
Secondary (Shield) Supply System				
Type of Cooling	GHe	GHe	GHe	GHe
Nominal Inlet Temperature (K)	40	40	40	40
Nominal Outlet Temperature (K)	< 55	< 55	< 55	< 55
Max. Allowable Pressure (atm)	20	20	20	20
Heat Load – Calculated (Used) (W)	33.76 (44)	43.73 (44)	89.08 (90)	131.20 (132)

1. The first sets of elements, the eyepiece and condenser magnets serve to expand the beam to a size appropriate for object illumination. Monitor lenses, each consisting of four quadrupoles, which identically transfer the expanded beam onto the object, follow the condenser magnets and are located just upstream of the study object. The monitor lenses provide a means of measuring beam properties at a distance from the object. Although the monitor lenses are a baseline of the project, alternative means of beam diagnostic are possible. If monitor lenses are not included, the condenser and eyepiece magnets are moved closer to the object. Two lenses sets, each consisting of four quadrupoles, are located immediately downstream of the study object. Each set provides an image of the object. Adjoining pairs of quadrupoles share the same cryostat. The magnets of each four-quadrupole lens set are powered serially. Finally, the condenser and eyepiece magnets are independently powered.

The lens SC elements are the lens magnets (small and large bore) and condenser magnets (small and large bore). The eyepiece magnets are normal conducting and operate at room temperature. TABLE 1 presents the parameters used to develop a baseline cryosystem for the SC magnet lens system. The low atmospheric pressure of Los Alamos, elevation 7,000 ft. (2,100 m) above sea level, allows magnet operation at temperatures below 4.5 K without warm vacuum pumping or cold compressors. The lower operating temperature permits a more aggressive magnet design, a larger quench margin, or some of each. Magnet heat loads were developed by linearly scaling the measured and calculated values of the CEBAF (Continuous Electron Beam Accelerator Facility) Hall C quadrupole magnets [5,6] by length and bore radius. The numbers in the brackets beside the scaled numbers are the values of heat load used in the cryoplant-sizing calculations. The use of liquid nitrogen to cool the magnet shields located at tunnel level is avoided to minimize facility oxygen-deficiency safety concerns. Liquid nitrogen is, however, used to precool the helium in the grade-level cryoplant.

THE CRYOGENIC DISTRIBUTION SYSTEM

The configuration of the lens system lines resembles a crossroad of twelve evenly spaced one-way roads (the magnet lens beams), each road entering and passing through the intersection (the object), from right to left, see FIG 1. The baseline distribution system has a cryoplant at grade level that is connected to the lens lines 50 m below grade (tunnel level). The outgoing flow of cryogens is divided at tunnel level into clockwise (CW) and counter clockwise (CCW) transfer-line headers routed around the outer perimeter of the gallery (assumed 33 m radius, FIG 2) at 3 to 6 m above the tunnel floor. Valve boxes direct distribution-header flows to the (parallel) individual lens feed lines. The lens-line connections may be removable bayonet jumpers or hard-plumbed transfer lines. The lens-line magnet vacuum vessels, rather than transfer lines, supply the insulating vacuum for cryogen transport between the individual magnets.

FIG 3 is a flowsheet of the lens cryogenic distribution system. Cryoplant supercritical helium at about 4 atm flows to parallel JT valves, feeding the lens-line magnets with two-phase helium at 4.43 K and covering the magnets with liquid. Most of the flashed gas and heat-load boiloff is returned cold to the cryoplant cold end in a low-pressure return line at < 1.2 atm. The balance of the cold gas is returned to compressor suction (0.9 atm) after being warmed in vapor cooled current leads. Lens-lines' magnet shields are cooled in series. Cooldown of lens-line magnets and their shields is performed serially until the shields reach operating temperature. This configuration permits independent cooldown and warm-up of a single line or of multiple lines in parallel.

Running the tunnel-level-transfer line header in the cross tunnel (63-m radius assumed) was considered, but requires more transfer line, and thus higher system capital costs, higher heat loads and higher operating costs.

The cryoplant has been positioned on an axis (y = 0 in FIG 1 and 2) so that the heat loads, cryogen flows and transfer lines are essentially symmetric about the facility axis.

CRYOSYSTEM CAPACITY AND REQUIREMENTS

TABLE 2 presents the system heat loads and utility requirements for the baseline design and the three other cases considered. Transfer-line heat loads of 0.5 W/m at 4.43 K and 1.91 W at 47.5 K were assumed. These distributed numbers include the heat loads for valves, bayonets, etc. The following margin factors are used in the table: primary (4.43 K)

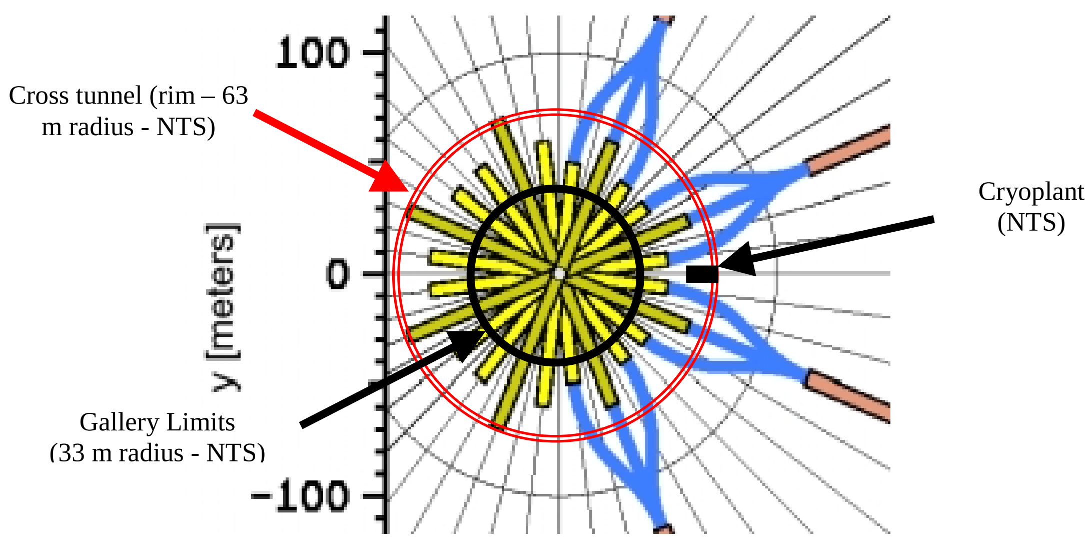

FIGURE 2. The magnetic lens system. NTS – Not to Scale

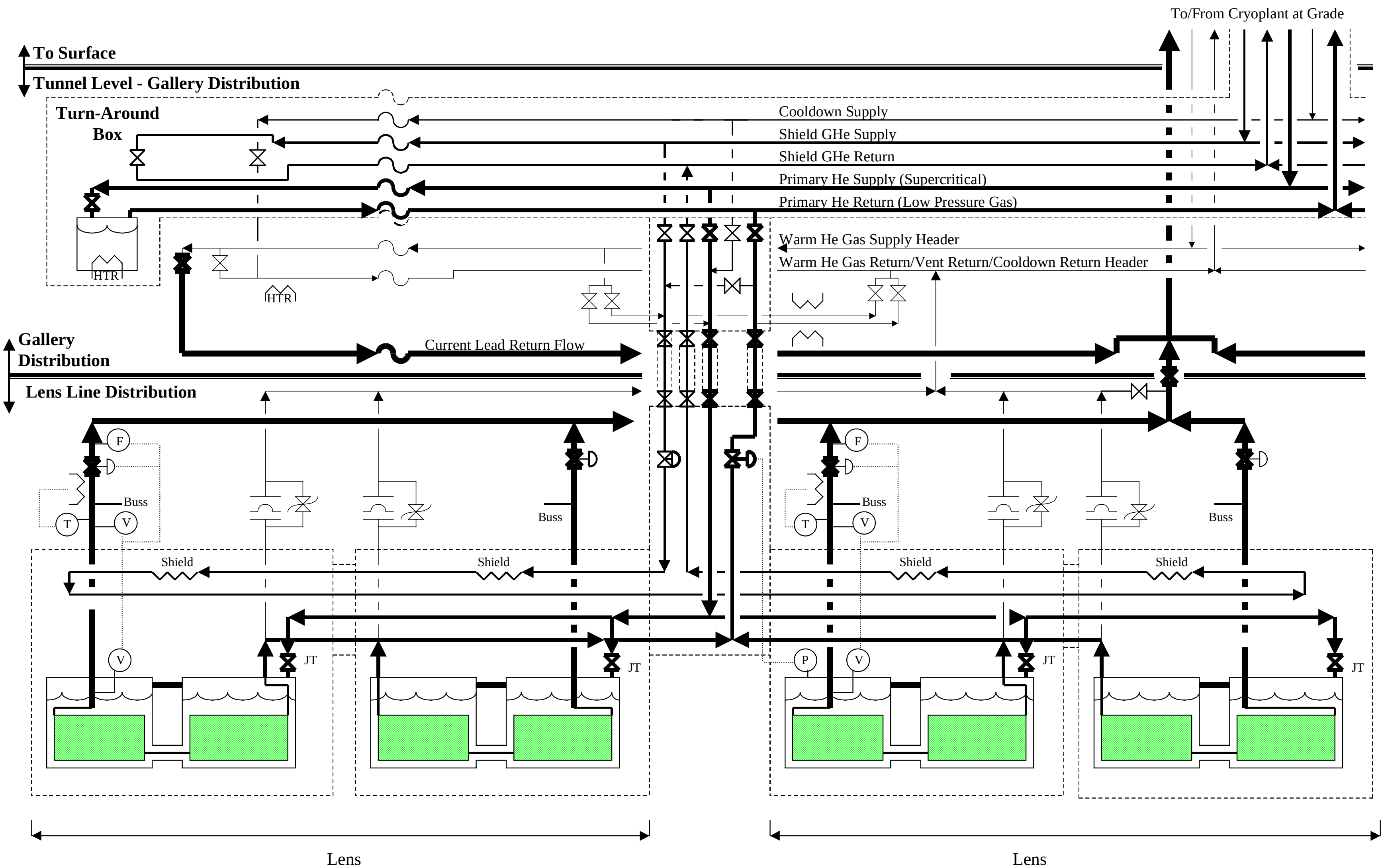

FIGURE 3. The Lens System Cryogenic Distribution System.

heat loads, 1.3; liquefaction load, 1.2; and shield heat load, 1.5. The total equivalent heat load at 4.5 K[1] contains an additional factor of 1.2 to provide a system-control margin. The efficiencies used are 0.23 and 0.3, respectively for 4 K and 47.5 K refrigeration. The total equivalent 4.5 K heat load for the baseline design is 13,440 W.

TABLE 2 indicates that placing the distribution header in the cross tunnel increases the total equivalent heat load of the system by roughly 10% with or without monitor lenses. Additionally, the total transfer-line lengths and costs are significantly impacted. For these reasons, placing the distribution header in the cross tunnel was eliminated from further consideration.

CRYOSYSTEM CAPTIAL COSTS, FACILITY AND UTILITY REQUIREMENTS

TABLE 3 summarizes the capital costs, and the utility and facility requirements for operating the lens-system cryoplant with a gallery-located distribution header. The parameters for the alternate approaches, with and without monitor lenses, are presented.

The cost basis is the Strobridge correlation relating cryoplant costs to the total equivalent heat load at 4.5 K [7,8]. The correlation coefficient was determined using the known cost of a turn-key system purchased for the Superconducting Super Collider Project [9] and corrected for inflation using the Marshall and Swift Equipment Cost Index. The cryoplant cost numbers include warm-helium-gas storage, warm compressors with oil-removal system, gas dryers, cold boxes, control system, and liquid-helium and liquid-nitrogen storage. The cryoplant cost numbers also include transportation to Los Alamos, and installation and commissioning by the cryoplant vendor as a turnkey system. They do not include building and other facility costs, and assume utilities are provided to stub-ups located near each of the skids.

Transfer-line costs were determined using per linear-meter cost numbers, corrected for inflation, achieved by the CEBAF cryogenic distribution system [10] and include transfer-line lengths and end boxes, and installation and commissioning. Spare-part costs are taken to be 10% of the cryoplant costs.

Electrical power consumption was determined by the Carnot relationship and an efficiency for a real refrigerator operating between 4.5 and 310 K where the heat removed by the refrigerator is the total equivalent heat load at 4.5 K. An efficiency of 23% of Carnot was used.

TABLE 2. Heat loads for the AHF lens system's cryoplant for the four cases considered. Column in bold type is the baseline system.

Header Transfer Line Location	Gallery	**Gallery**	Cross Tunnel	Cross Tunnel
Monitor Lens	No	**Yes**	No	Yes
Total Transfer Line Length (m)	930	**780**	1520	1340
Primary Heat Load @ 4.43 K[1] (W)	3,810	**4,660**	4,580	5,380
Liquefaction Load[1] (g/s)	37.4	**49.9**	37.4	49.9
Shield Heat Load @ 47.5 K[1] (W)	17,320	**21,750**	20,720	24,950
Total Equiv. Heat Load @ 4.5 K[2] (W)	10,550	**13,440**	11,760	14,590

[1]The following margin factors were used and are reflected in the table: 1.3 for the primary (4.43 K) heat loads, 1.2 for the liquefaction load, and 1.5 for the shield heat load.
[2]The total equivalent heat load at 4.5 K contains an additional factor of 1.2 to provide a system control margin.

[1] The total equivalent heat load at 4.5 K is the industry accepted standard for comparing refrigeration systems operating at different temperatures and liquefaction rates. The loads at 4.43 K, shield temperature, and the liquefaction loads are thermodynamically converted to an equivalent load at 4.5 K.

TABLE 3: Capital costs, utility and facility requirements to operate the lens cryosystem, with and without monitor lenses.

Transfer Line Location	Gallery	Gallery
Monitor Lens	None	As required
Total Transfer Line Length (m)	930	780
Total Eq. Heat Load @ 4.5 K (W)	10,550	13,440
Cryoplant Cost[1] ($)	18.3 M	21.7 M
Transfer Line Costs[1] ($)	4.12 M	3.47 M
Spare Parts ($)	1.83 M	2.17 M
Total Capital Costs ($)	*24.25 M*	*27.34 M*
Wall Power (MW)	3.11	3.97
Nitrogen Consumption (Gal/Day)	4650	5930
Water Consumption	Minimal	Minimal
Compressor Building Size[2] – area (height) [ft^2 (ft)]	5,250 (20-30)	6,700 (20-30)
Cold Box Building Size[3] – area (height) [ft^2 (ft)]	4,000 (35-50)	4,000 (35-50)

[1]Purchase order price for a turnkey system. Does not include building costs. Assumes utilities provided to stub-ups at skid locations.
[2]Contains the compressors and oil removal systems. Noise level ~ 95 dB. An overhead crane (5-10 ton) services the compressor skids.
[3]Contains cold box, control room and electronics room.

Liquid nitrogen consumption was determined by scaling, using the ratio of the known nitrogen consumption of existing systems [9] with respect to their total equivalent heat load (about 14 W at 4.5 K per liter/hr of liquid nitrogen).

A compressor room houses the warm compressors (with oil removal), and the gas dryer(s). The compressor-room size was determined by scaling, using the ratio of the known horsepower of the HERA (Hadron Electron Ring Accelerator) compressors with respect to the size of the building housing these compressors [11].

The cold-box room uses the CEBAF cold box room size as a reference with allowance made for the control system and control room. A vertical cylindrical cold box is assumed.

Helium-gas compressors will be equipped to ambient-air cool the oil and gas, and consume no water. Small amounts of water will be required for turbine brakes.

SUMMARY

The development of the helium refrigerator/liquefier size and site position, and the distribution system parameters for the large-bore pool boiling, SC magnetic lens system are presented. Options using a cross-tunnel based distribution header were eliminated from consideration for heat-load and transfer-line-length reasons. A gallery-based distribution header is recommended. Costs, utility, and facility requirements for the cryosystems with a gallery-based distribution header, and with and without monitor lenses are developed. The inclusion of monitor lenses in the lens lines depends upon detailed experimental considerations. The baseline configuration assumes monitor lens pending completion of the beam dynamics work.

Including the monitor lenses, the recommended cryoplant size is about 13-kW at 4.5 K. Total capital costs for the complete cryosystem are approximately $27 M. Power and liquid nitrogen requirements are roughly 3.93 MW and 5,900 Gal/Day, respectively.

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