Title
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Publication Date
1972-09-01

Presented at the Conference of
the Cryogenic Society of America,
Chicago, IL, Oct. 3-5, 1972

LBL-1316

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September 1972

AEC Contract No. W-7405-eng-48

LBL-1316

Cryopumping a Large Accelerator*

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September 1972

Abstract

A cryogenic vacuum pump, designed to lower the base pressure from $2\mathrm{x}10^{-6}$ torr to $3\mathrm{x}10^{-7}$ torr was installed in the Bevatron in February 1972. The Bevatron, a particle accelerator at the Lawrence Berkeley Laboratory, contains approximately 11,000 ft^3 of free volume and an excess of 100,000 ft^2 of outgassing surfaces pumped by 24 freon-baffled 32-inch oil diffusion pumps. The gas loads consist of metallic and organic outgassing surfaces as well as air leaks from non-repairable radiation-hardened aged gaskets and mechanical actuators.

The magnitude and composition of the steady state gas loads were measured by pressure rates of rise, trapped and untrapped ion gage base pressures, and residual gas analyzer data.

Nine cryopanels were installed, fed by 20°K recirculating helium refrigerators and 80°K boiling liquid nitrogen. Monte Carlo computations predict noncondensible (at 77°K) pumping speeds of 140,000 liters/sec and condensible pumping speed of >500,000 liters/sec. Results of preliminary experimentation using liquid nitrogen and liquid helium in the system yielded pumping speed data and refrigeration load data within calculated estimates. Final measurements are included in this report.

Introduction

The Bevatron is a large synchrotron completed in 1954 at the Lawrence Berkeley Laboratory. Its main ring consists of four straight sections and four curved sections. Each curved section or quadrant consists of a rectangular tube approximately 4 ft x 1 ft x 75 ft long. Parallel to this "beam tube" is a 2 ft x 3 ft crawl space designed for personnel access. The straight sections are large steel tanks 10 ft x 8 ft x 20 ft long. The original pumping system has 24 32-inch oil diffusion pumps, six located in each of the four straight sections. Each pump is baffled with a freon-cooled Chevron-type shield maintained at -15°F to reduce oil backstreaming to the Bevatron. Typically, 16 to 20 of the 24 pumps are operating, with the balance valved off for maintenance, repair, or to defrost the baffles. Instrumentation in the Bevatron consists of an ion gage in each of the four straight sections and two of the four curved sections. Prior to cryopumping, typical pressures were 1 to $2\mathrm{x}10^{-6}$ torr in the straight section and $3\mathrm{x}10^{-6}$ torr in the curved sections. These pressures were obtained only after several months of pumping after the system had been up to air. This slow pumpdown rate severely restricted internal machine access, since this access had to be balanced against operating time at reduced beam current due to poor vacuum.

Design Objectives

It was always felt that increasing the pumping speed in the Bevatron would have a positive effect on the proton beam current. However, with the advent of the heavy-ion program at LBL the quality of the vacuum took on new importance. Pumpdown rates became an important consideration also, because of the anticipated need for more frequent changes of equipment inside the Bevatron vacuum envelope. The general requirements were to decrease the Bevatron base pressure by about a decade, and in the process, increase the pumpdown rate.

Gas Load

The Bevatron consists of 11,000 ft^3 of free volume with approximately 25,000 ft^2 of free outgassing area. The magnet pole tips,

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*Work done under auspices of the U. S. Atomic Energy Commission.

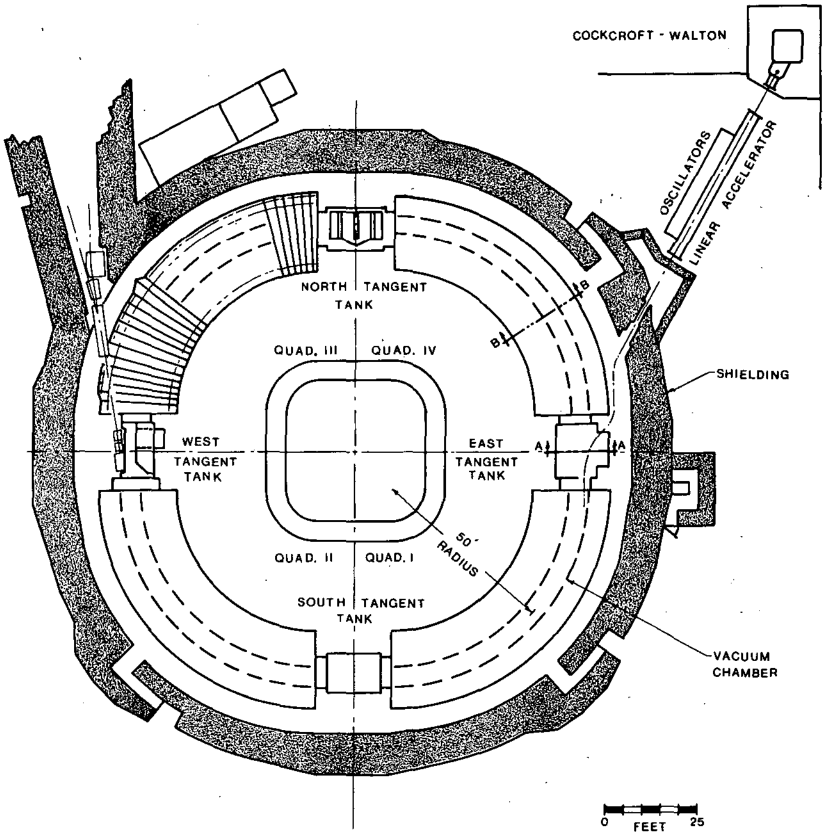

Fig. 1. The Bevatron.

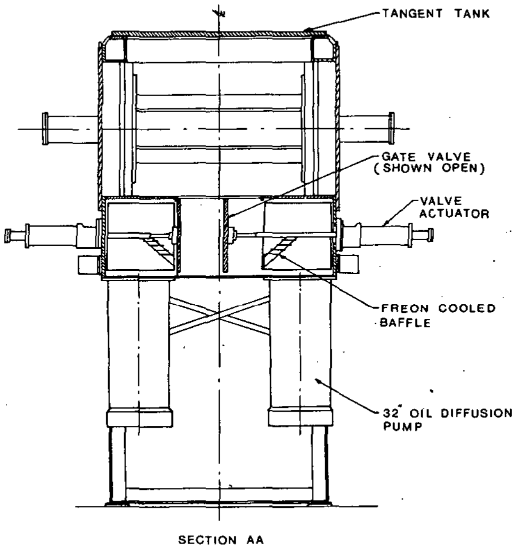

Fig. 2
Tangent tank and diffusion pumps.

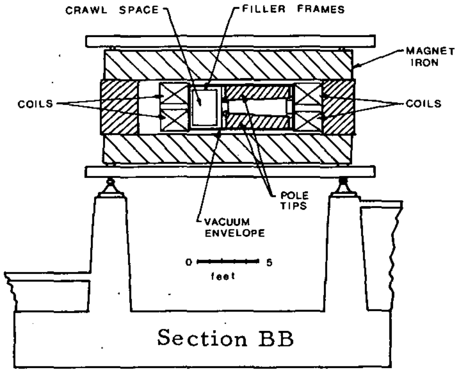

Fig. 3
Quadrant cross section.

which consist of about 7,000 0.50-in.-thick enameled steel laminations, add approximately 80,000 ft^2 of restricted outgassing area. Radiation-hardened gaskets add to the gas load by providing small air leaks which are repaired periodically with "dux seal" (many of these gaskets are inaccessible except by major overhaul of the machine). Generous quantities of epoxy fiberglass and other plastics, as well as long-stroke reciprocating mechanical actuators, also add to the gas load problem. A large percentage of the free surfaces of the inside of the vacuum envelope are rough steel surfaces and aluminum castings which act as strongbacks; these have soaked up some quantity of the backstreamed pump oil over a period of years.

Measurements

Design of an improved vacuum system required a knowledge of the quantity, quality, and distribution of the gas load. The quantity of the gas load was measured by a simple pressure rate of rise technique. This measurement compared favorably with the computation of the load by using the measured average base pressure of the vacuum envelope and estimates of the net speed of the diffusion pumps at that pressure. The data varied between 45 to 100x10^{-3} torr-liters/sec, and were rather well clustered around 60x10^{-3} torr-liters/sec.

A knowledge of the quality of the residual gases is crucial to the design of many types of vacuum systems because of the highly selective pumping characteristics of different pump types. Residual gas analyzer data showed relatively large and fairly equal peaks at mass 18 and mass 28, corresponding to large populations of air and water. Smaller peaks in the high-mass range plus a peak for mass 1 indicated the presence of hydrocarbons and the hydrogen ionized from these hydrocarbons.

Measurements at each straight section revealed that a factor of 2 pressure reduction was achieved by adding liquid nitrogen shielding to the ion gage. In general, we concluded from the above results that the residual gas was approximately half water and other condensibles and half air.

Since the distribution of the gas load would dictate the pump location, this measurement also became crucial to the design. The relative quantities of the gases in the four straight sections were simple to measure from relative base pressures of the tangent tanks. The proportion of the gas in the curved sections was a more difficult measurement: a nude ion gage was mounted on a travel target assembly, inserted through an air lock, and traversed through a quadrant. The monitored pressures were plotted against position, and the plot displayed the characteristic parabolic shape of a pipe with uniform gas generation pumped only at its ends. The data points were least-squares fitted to a parabola whose coefficient of the second-order term could be related to the gas load according to the following expression:

$$p = \frac{Q_T X^2}{2 C_T \ell^2} + C_1 X + C_2 ,$$

where

$$C = \frac{Q_T}{2 C_T \ell^2}$$

and

p = pressure (function of X),

Q_T = total gas load in the curved section (torr-liters/sec),

C_T = conductance of the rectangular pipe length ℓ (ℓ/s),

ℓ = length (units same as X in parabolic equation).

The conductance, C_T, was estimated from a standard geometric formula. Figure 4 shows a surprisingly close fit to a parabola of data taken on a day when system pressures were unusually high. The results of this experiment indicated that approximately half the gas load occurs in the curved sections and that a serious pressure gradient existed because of the relatively low through-put of the curved section to the straight sections where the diffusion pumps supplied the only molecular sink.

Summary of Design Parameters

1) Gas load $\cong$ 0.060 torr-liters/sec.

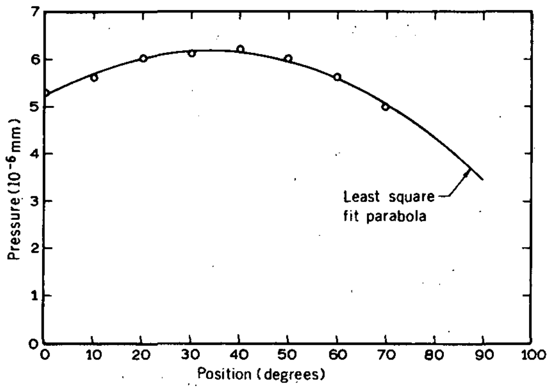

Fig. 4. Parabolic pressure distribution in quadrant.

2) Half the gas load is noncondensible at 77°K.

3) The gas load is fairly uniformly distributed about the perimeter of the Bevatron.

4) The desired base pressure is 2 to 3×10^{-7} torr.

5) Any LN_2-shielded 20°K pumping surface will necessarily have a high "condensible" pumping speed compared to its air speed. Thus, the design requires careful sizing of the air pumping speed:

$$S_{req} = \frac{Q_{total/2}}{P_{req}} = \frac{60\times10^{-3/2}}{3\times10^{-7}}$$

$$= 100,000 \text{ liters/sec.}$$

Cryopanel Design

A two-dimensional Monte Carlo computer program was devised so that accurate predictions of the pumping speed of the final geometry could be made. Monte Carlo techniques trace the orbits of a large population of particles being emitted, reflected, lost, or absorbed in a two-dimensional array of straight lines and circles. A census is then taken of the particles lost or absorbed to determine the capture probability of a particular geometry. The Monte Carlo computation of the geometry shown on Fig. 5 yielded a capture fraction of 0.2683.

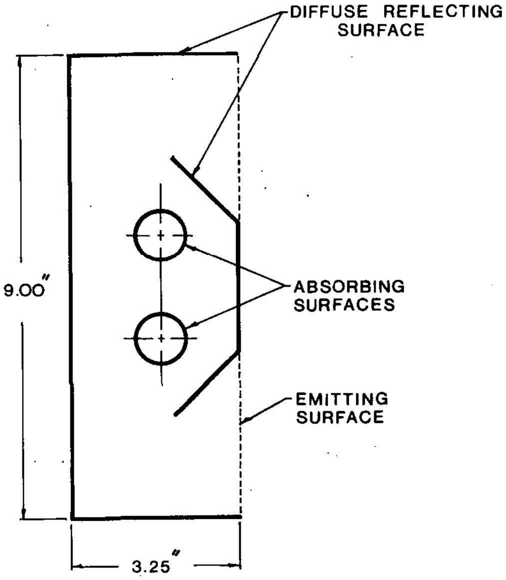

Fig. 5. Monte Carlo model.

Pumping speed computations based on this capture fraction are computed as follows:

$$S = C_p \times \ell_e \times s = 131 \text{ liters/sec-in.}$$

where

S = pumping speed per inch length of panel,

s = "blackhole" speed,

C_p = capture fraction,

ℓ_e = length of the emitting surface.

Preliminary tank measurements of a 60-in.-long test panel confirmed this capture probability within 5%. Nine cryopanels, each 10 ft long, are positioned in the Bevatron as shown in Fig. 8.

Heat Loads

The nine cryopanels have a computed total "air" pumping speed of 140,000 liters/sec. The convex perimeter of the cryopanel is 24.5 inches. Assuming 90 ft of cryopanel, a curve for the emissivity of a polished surface as a function of water cryodeposit is entered. The emissivity computed for two to three days of operation at the fairly high vacuum load levels anticipated yielded emissivities of 0.2 to 0.4. Because hydrocarbons make up a fair fraction of the gas load, and since periodic regeneration of the cold surfaces by temperature cycling becomes problematical because of the low vapor pressure of these hydrocarbons, a conservative value for emissivity of 0.5 was used in our computations.

Heat load = $A \epsilon h$,

where h = black-body radiation from 77 to 310°K = 0.384 watts/in.^{2}.

Heat load = 90 x 12 x 24.5 x 0.5 x 0.384 = 5080 watts ≅ 115 liters/hour LN_2 consumption.

Operating cost at this rate for a machine which operates continuously would be too high. Therefore, six layers of multilayer insulation were wrapped on all the external surfaces. The LN_2-cooled perimeter which looks directly at the warm vacuum chamber was thus reduced to 4.72 inch/inch of panel. The inside surface of the LN_2 shield was painted a dull black to prevent reflection to the 20°K surface. The black-body heat load is reduced to approximately 2 kW or LN_2 consumption rate of 45 liters/hour. For this geometry, the "condensible" pumping speed is about 400,000 liters/sec. Thus, the partial pressure of condensibles in the vacuum system should be approximately 7.5×10^{-8} torr. In addition to the 90 ft of cryopanel, there are 264 ft of transfer lines inside the vacuum space and 70 ft of external transfer lines. The internal helium lines are LN_2-shielded and the external lines are insulated with multilayer insulation against radiant heat transfer.

Circuit Design

There are four circuits in the cryopanel system. Three circuits feed two cryopanels, and the fourth circuit feeds three. Two CTI 1400 refrigerators each feed two circuits. Two refrigerators were chosen although a single refrigerator would have had enough capacity. Reasons for deciding on two refrigerators follow:

1) Uncertainties existed in the calculated refrigeration loads due to eddy current heating and lack of precise pressure drop data. The reserve capacity was built in to take care of unanticipated contingencies.

2) A finely tuned feedback control system would be required to balance the flow if a single refrigerator fed four branching circuits. The precision of this balancing procedure becomes very critical if the load approaches the full capacity of the refrigerator, especially since the vapor pressures of N_2 and CO are a sensitive function of temperature in the 20 to 25°K range.

3) Redundancy in the circuit allowed the operation of half the cryopump system in the event of refrigerator outage.

4) Operational experience will establish accurate refrigeration load values. Expansion of the system then becomes a possibility, since in any vacuum system the vacuum is seldom "good enough."

The CTI units offered a range of refrigeration capacities between 100 and 350 watts at 20°K, depending on choice of options (LN_2 pre-cool and an extra compressor). Since the refrigerator circuit is not separate from the circulating fluid, the compressor provides the driving force in circuits with up to 220 ft of 0.310-i.d. line. These and other features made this unit attractive, especially in view of the possible expansion of this system.

Design Constraints

The constraints imposed by the physical characteristics of the Bevatron and the operating schedule presented some unique challenges.

1) A three-week period was set aside for the Spring of 1972. Design, fabrication, and inspection of all components to be installed in the vacuum envelope had to be completed before this shutdown. All installation and leak checking had to be completed in that period.

2) Residual radiation limited the amount of access time for any installer.

3) The extreme congestion of some of the areas required some fairly complex designs.

4) The maximum circuit length is 105 ft. Rather generous expansion joints were required between fixed points (usually the

cryopanels) in the transfer line to handle the thermal shrinkage.

5) Space, clearance, and access problems required a large number of joints in the vacuum space. The time factor and lack of working space made the prospect of soldering or welding extremely unattractive. Thus, a reliable mechanical joint technique had to be selected which could withstand numerous temperature excursions.

Mechanical Design

Figure 8 shows the location of the cryopanels in the Bevatron. Six cryopanels are located in the quadrants and three are mounted in the tangent tanks. A cryopanel was omitted in the north because of the physical clearances required by the high-voltage r.f. accelerating electrodes mounted in this tank. The extra panels in quads III and IV near the tank handle the pumping required in the north. Cross sections of the quad panel and the tangent tank panel are shown in Fig. 6.

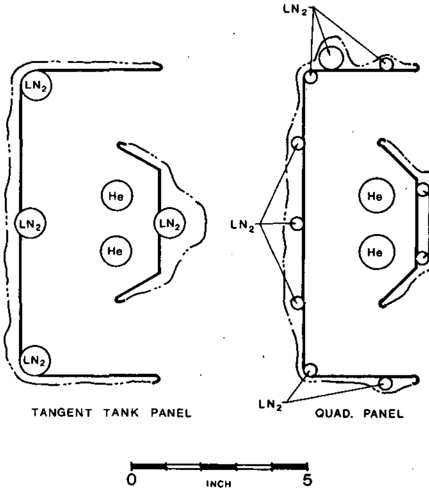

Fig. 6. Cryopanel cross sections.

The time-varying magnetic field dictated both the radial location and the materials of construction of the cryopanels mounted in the quadrants. The quad panels were mounted in the crawl space to avoid the high-field areas. These panels were made from stainless steel to minimize the eddy current heat loads generated by the time-varying magnetic field in the quadrants. The use of stainless steel required close spacing of the LN_2 circulating tubes because of low thermal conductivity. Copper was used in the tangent tank panels where eddy current heating was negligible, thus allowing simpler construction because of more generous spacing of the LN_2 tubes. The deeper panels provided a slight increase of the capture fraction.

Inside the vacuum envelope there are 16 sections of transfer line of two basic types as shown in Fig. 7. The helium lines in the quad transfer lines were wrapped with alternate layers of aluminized Mylar and nylon mesh. The quad lines were comparatively long and straight and could easily be wrapped with the superinsulating material. This material acted as a physical spacer between the 80°K surface and the 20°K surface, as well as a radiant insulator.

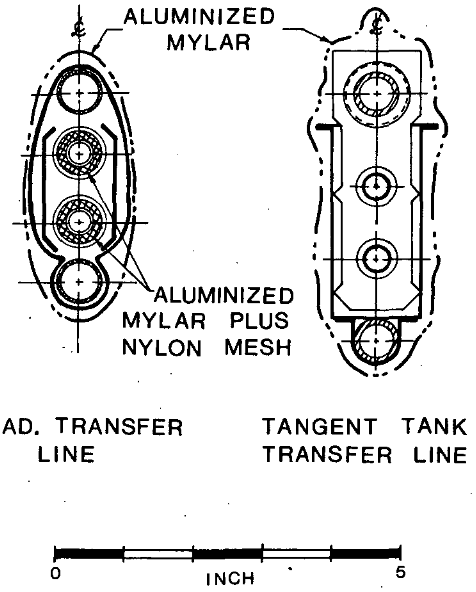

Fig. 7. Transfer line cross sections.

Most of the expansion joints and all of the severe bends occurred in the tangent tank transfer lines. Here, physical separation between the LN_2 lines and 20°K He lines was achieved with plastic spacers and plastic grommet inserts. These transfer line sections vary from 30 to 2.5 ft long, depending on their ease of installation. There are 20 joint sections connecting the various lengths of transfer line and cryopanels inside the vacuum envelope. Each joint section contains four unions: a feed and return for both LN_2 and helium. The "Conoseal" union was selected because it is almost foolproof in installation and extremely reliable during the numerous temperature cycles required during operation. This union features a nickel gasket compressed between two stainless steel glands with a smooth raised ridge. Relatively high torques are required in installation areas with very limited working space. Therefore, a special tool was designed with a 10:1 mechanical advantage in torque which prevented relative rotation of the glands during the torquing (Fig. 13).

Circuits

The helium and nitrogen circuits are shown in Figs. 8 and 9. Splitter boxes are mounted on the east and west tangent tanks where flows for the helium circuit are controlled with broken-stem valves. Gas bulb thermometers for each of the input and output lines are provided for balancing the flows.

Performance

The cryopanels were installed in the Bevatron in February 1972. Liquid nitrogen was circulated in the LN_2 circuits for the first time on February 25, 1972. The external helium transfer lines were installed during a two-week shutdown in June 1972. The refrigerators were installed in July, and cold gas was circulated in the helium circuits for the first time on August 2, 1972. Figure 10 illustrates the average pressure history in the Bevatron during this initial period. The Bevatron has been up to air once since the initial run with 18°K helium. In addition, the nitrogen and helium circuits have been warmed up several times to dry off the panels against the diffusion pumps.

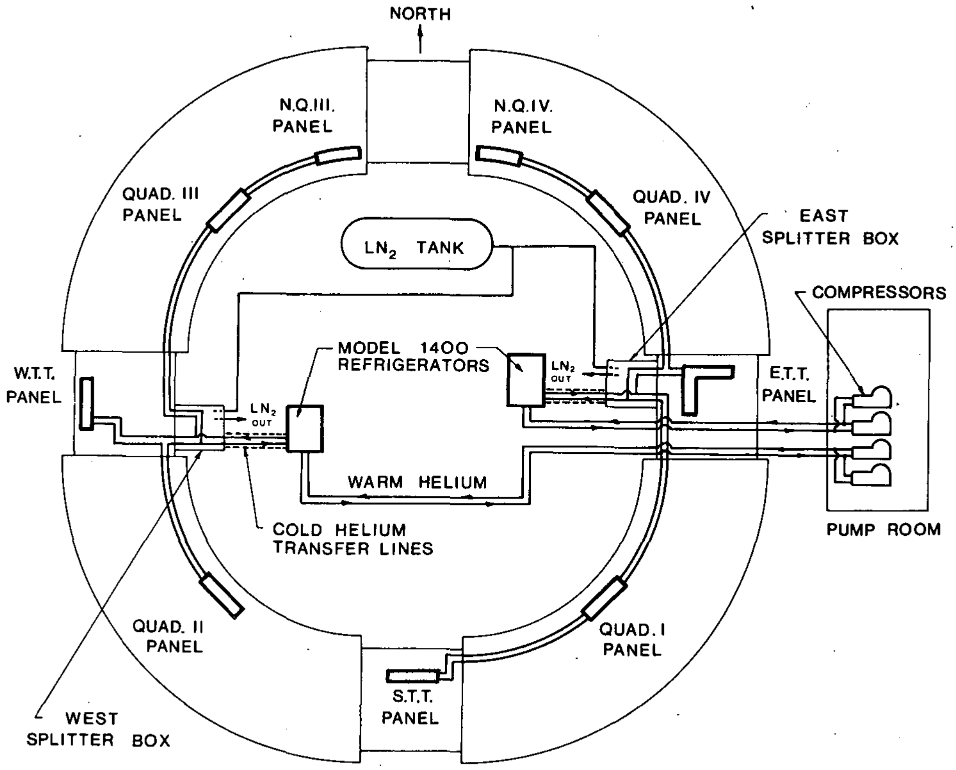

Fig. 8. Cryopanel and gas distribution layouts.

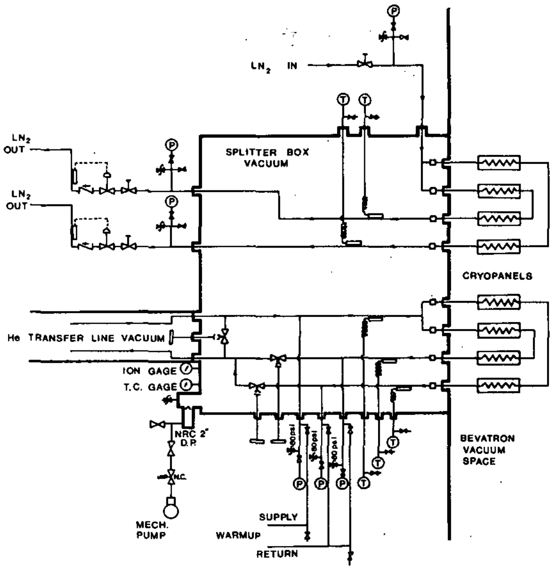

Fig. 9. Splitter box circuit detail.

In general, good operating pressures (2 to 4×10^{-6} torr) have been achieved within a few hours after introduction of LN$_2$. Previously, several weeks were required to achieve equivalent pressure after the vacuum tank had been up to air. Introduction of 18°K helium reduced the pressure by a factor of 2 below the base pressure achieved by LN$_2$ alone. Thus far, the best average pressure achieved with the full system has been 3.0 to 5×10^{-7} torr.

It should be noted that the vacuum performance described above does not reflect the full capability of the cryopump system. There has not been any extended period under vacuum to allow the outgassing rate to base out. Previous data have indicated that two months is required for the tank to dry out. Also, there are several leaks in the vacuum tank system which have not been adequately repaired.

Thus far, we have not been successful in holding a base pressure in the 10^{-7} torr range when we close the gate valves on the diffusion pumps. At these pressures, the net pumping speed of the diffusion pumps should be between 5 and 10% of the cryopanel pumping speed. A slow pressure rate of rise with the D.P. gates closed is interpreted as a verification of the existence of air leaks and the introduction of the fractions of air (24 ppm neon, helium, and hydrogen) which are not pumped at 20°K.

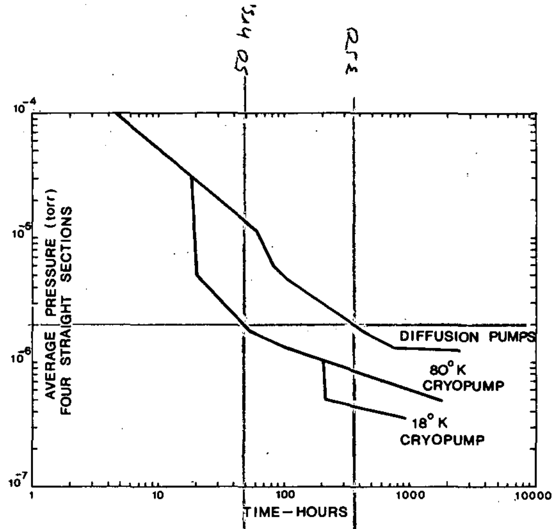

Fig. 10. Pumpdown curves.

The press of heavy-ion and high-energy physics experiments in the Bevatron has not allowed time to perform the obvious residual gas analyzer experiments to supplement the rather crude experiments related above.

The refrigeration load has been close to predicted design calculation. Eighty watts is the estimated load on each of the two helium refrigerators operating in the circuit, based on return gas temperature of 15°K and supply temperature of 12°K. The total measured consumption rate of LN$_2$ is 70 liters/hour. Presently, the LN$_2$ circuit is a once-through circuit which operates on a temperature sensor demand feedback control system. The consumption rate thus depends on how closely this system can be adjusted to most efficient setting. A recirculating system is planned which should reduce the LN$_2$ consumption.

Conclusion

Given sufficient time under vacuum to allow the substantial outgassing area of the Bevatron to base out, and assuming that future effort will be successful in pinpointing and repairing some of the more obvious leaks, the design pressure of 2 to 3×10^{-7} torr should be achieved.

Refrigeration loads fairly close to design prediction allows us a fair degree of confidence in our ability to expand this system or design new systems. There is nothing quite like an empirical datum point to extrapolate in the design process.

Acknowledgments

We would like to acknowledge the leadership provided on this project by Walt Hartsough, Hermann Grunder, Ken Lou, and Bob Richter. It would be difficult to acknowledge all the effort spent in design, procurement, fabrication, and installation. However, we would like to express our gratitude to the large group of individuals who have expended extra effort to bring in a good job on time.

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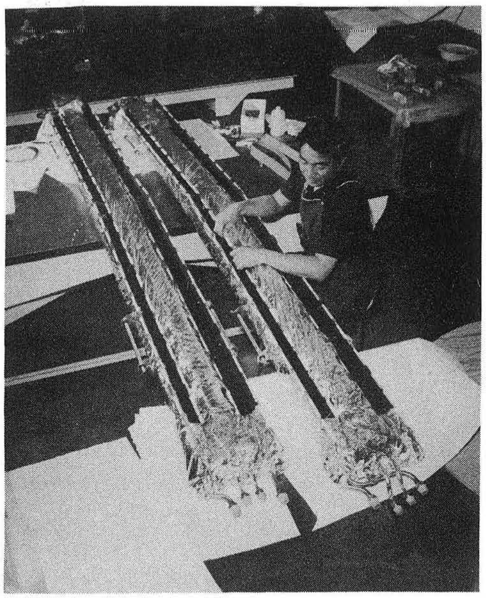

Fig. 11
Quadrant cryopanel assemblies with multilayer insulation.

Fig. 12
Quadrant transfer lines.

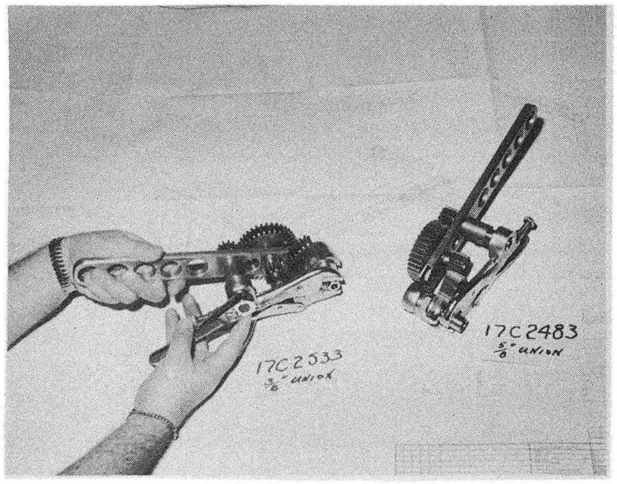

Fig. 13
"Conoseal" union torquing tool.

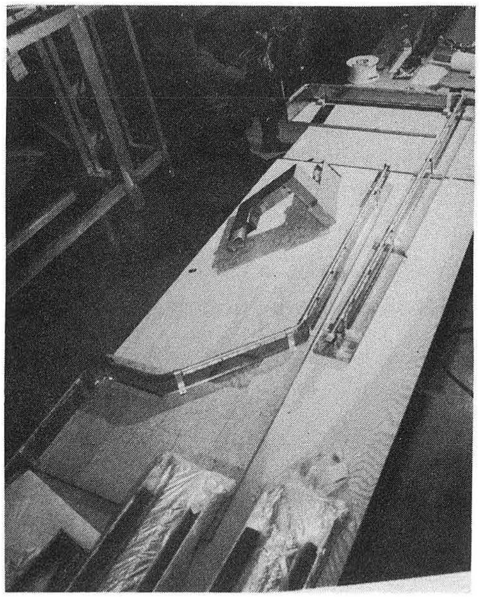

Fig. 14
Tangent tank transfer lines
(LN_2 feed and shield assembly)

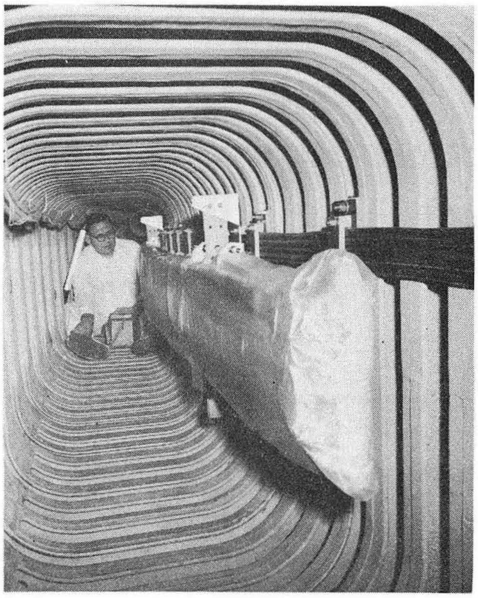

Fig. 15
Installed quadrant cryopanel.

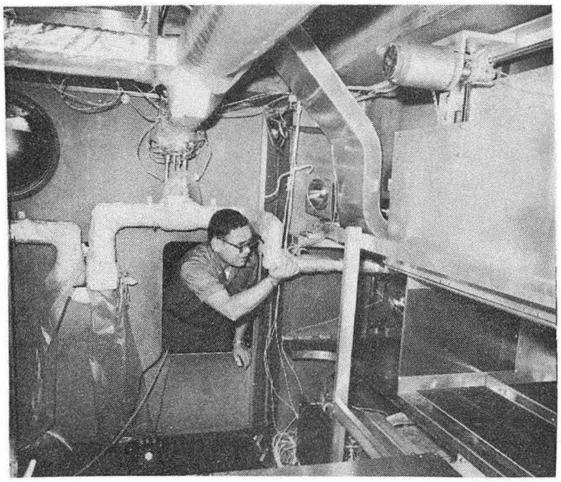

Fig. 16
East tangent tank transfer line installation.

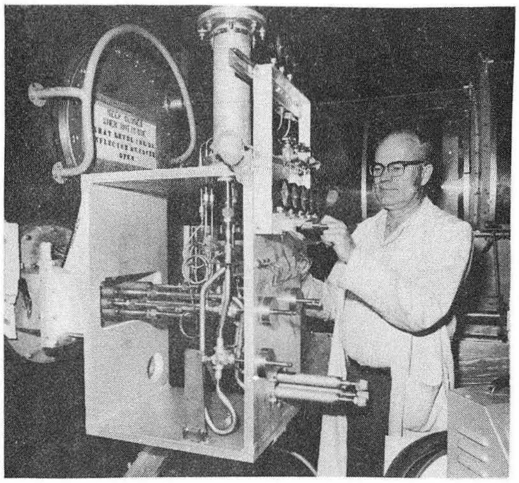

Fig. 17
East splitter box.

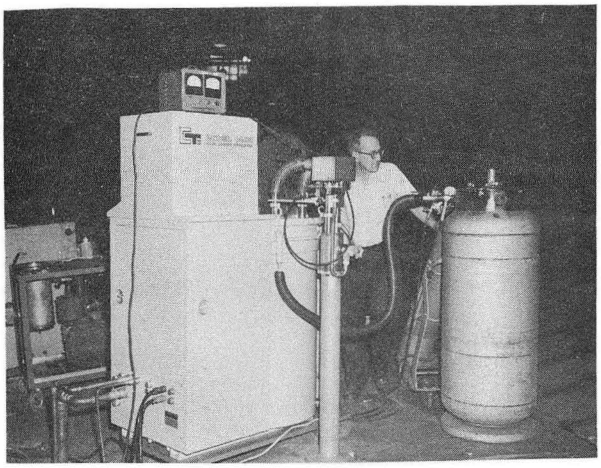

Fig. 18
East refrigerator installation.

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