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Publication Date
1971-02-01

Presented at the Particle
Accelerator Conference,
Chicago, Ill., March 1-3, 1971

UCRL-20197
Preprint

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February 1971

AEC Contract No. W-7405-eng-48

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A CRYOGENIC PUMPING SYSTEM PROPOSED FOR THE BEVATRON*

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Summary

A cryogenic pumping system capable of pumping 300,000 l/sec of nitrogen is proposed for the Bevatron to decrease the base pressure from $\sim 2 \times 10^{-6}$ to $\sim 2 \times 10^{-7}$ torr. The Bevatron consists of approximately 10,000 ft^3 of free volume with approximately 15,000 ft^2 of free outgassing area. The magnet pole tips, which consists of 1/2-in. laminations, add a potential 80,000 ft^2 of outgassing area. The design calls for an approximately 360-ft-long, 20°K surface shielded by an 80°K surface strung along the inside perimeter of the Bevatron. Initial design considerations indicate that radiant heat flux from the 80°K surface is a prime design factor which could greatly affect the operating and installation costs of 80°K refrigeration. A two-dimensional Monte Carlo type program was devised and used to optimize designs with maximum nitrogen pumping speed and minimum 80°K shield area to reduce the refrigeration costs.

Introduction

The Bevatron main ring consists of four curved sections and four straight sections. Each straight section is pumped by six 32-in. oil diffusion pumps baffled with freon-cooled chevron-type baffles maintained at -10 to -20°F to prevent oil backstreaming into the Bevatron. The curved beam tube cross section is a rectangular tube approximately 4 x 1 ft; it is about 75 ft long and is pumped only at the ends by using the diffusion pumps mounted in the straight sections. Parallel to this space is a "crawl space" designed for personnel access to the beam tube area which is approximately 2 x 3 ft in cross section and also pumped at the ends.

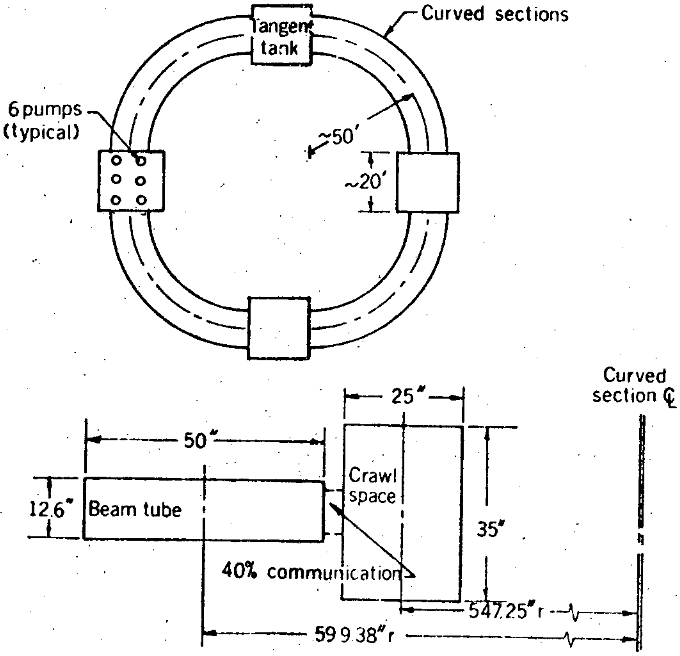

Fig. 1. Bevatron and curved cross section schematics.

Typically, 16 to 20 of the 24 pumps are operating with the rest down for maintenance and repair, including regular warmup and defrosting of the freon baffles. The vacuum space is instrumented with ion gages mounted one each in the straight sections and one in the center of a curved section. The typical base pressure readings from the gages under operating conditions range from ~ 0.7 to 2×10^{-6} torr in the straight sections and $\sim 2.7 \times 10^{-6}$ torr in the center of the curved section. At these pressures the diffusion pumps are basing out to approximately one-third of their rated full capacity. Estimating the throughput of the baffles at 30%, we compute a present system pumping speed of approximately 30,000 l/sec. Moreover, the speed rating curves for these pumps show that these pumps will base out absolutely at 4.5×10^{-7} torr.

Design Objectives

It is hoped to attain an operating pressure of 1 to 2×10^{-7} torr in the Bevatron. Since a differential pressure of 1×10^{-6} torr in the center of the curved section above the tangent tank pressure exists, it is obvious that additional pumping must be done in the curved section. Space limitations in this area immediately rule out additional diffusion-pump and ion-pump techniques. Titanium sublimation techniques seemed unattractive because of the maintenance problems inherent in such systems and also because of the difficulty in controlling the migration of evaporated titanium in an area where laminated magnet pole tips are exposed to the vacuum. This left cryogenic pumping.

Measurements

Measurements of the quantity, quality, and distribution of the vacuum load were desired.

A rate-of-pressure rise technique was used to estimate the quantity of gas load. This measured quantity was later verified by taking equilibrium pressure distributions with pumps in each section turned off, which created a differentially pumped condition. Also, the transient pressure rise for each section, differentially pumped, was measured and analyzed. These measurements were compared with the load computed by using the base pressure and estimated pumping speed of the diffusion pumps. In all cases the measured value of the vacuum load agreed within ±30% of a mean value. These measurements ranged from 45 to 100×10^{-3} torr-l/sec. The results of what we judged to be the most reliable measurement technique (simple rate of rise) typically ranged around the 60×10^{-3} torr-l/sec value.

The quality of the vacuum load is crucial to the design of a cryogenic pumping system. In particular, we are interested in the relative proportions of residual gases in the vacuum load which are noncondensable or condensable on a 77°K surface. To a lesser extent we are interested in the relative amounts of particular species of gases since, obviously, a large concentration of gases not condensable at 20°K obviates the use of a practical cryogenic system.

Also, particular species of condensables affect the thermal radiation properties of the surface coated with them.

An LN_2 shielded ion gage installed in each tangent tank showed that a 2-to-1 pressure ratio existed without and with LN_2 shielding. Also, measurements made with two different types of residual gas analyzers showed relatively large peaks at mass numbers 18 and 28 of approximately the same corrected amplitudes, which would correspond to large populations of air and water in the residual vacuum. Some small peaks in the very high mass range, where the instruments are very insensitive, and a peak for mass number 1 were also detected. These peaks indicate the presence of heavy hydrocarbons and the hydrogen ionized from these hydrocarbons. The relative proportion of this species of gas in the residual vacuum is rather difficult to quantify with any degree of confidence. In general, we conclude that the residual vacuum is approximately half water and half air.

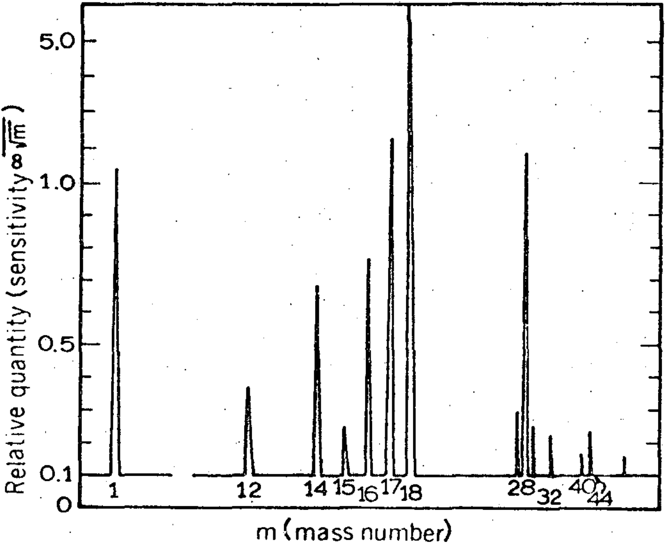

Fig. 2. Residual gas analysis of the Bevatron vacuum chamber gas pressure ~2 x 10^{-6} torr.

The relative quantities of the gases in the four straight sections were easy to measure from differential pressure measurements and from relative base pressures in each of the tanks. However, the proportion of the gas in the curved section was a rather more difficult number to measure. An experiment was performed in which a nude ion gauge was mounted on a travel target assembly and marched through two quadrants. 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. It should be noted that the pressure distribution presented in the figure was taken when the system pressures were unusually high. The data points were least-square fitted to a parabola which yielded the coefficients which could be related to the gas load. The gas loads computed in this manner seemed excessively large. Consideration of all the possible errors in the measured data and the assumptions made in the computations leads us to believe that the results of this experiment should be taken with a grain of salt. However, this experiment verifies the fact that a very serious pressure gradient does indeed exist in the quadrant and that pumping in the quadrant is imperative.

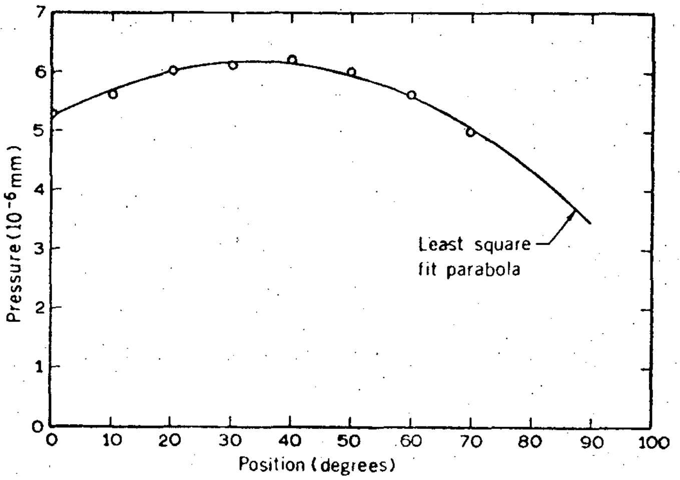

Fig. 3. Parabolic pressure distribution in the curved tank.

Design

The design parameters gleaned from the measurements thus far summarized and the design objectives are reviewed below.

1. Gas load ≈ 0.060 torr-l/sec.
2. Half the gas load is noncondensable at 77°K.
3. The gas load is fairly uniformly distributed about the geometry.
4. Desired base pressure ≈ 1 to 2 x 10^{-7} torr.

A proposed geometry for a distributed pumping system is shown in Fig. 4. This cross section is to be strung out along the inside perimeter of the Bevatron in the crawl space. Its length will be approximately 360 ft.

The required air pumping speed is

$$S_{req} = \frac{Q_{total/2}}{P_{required}} = \frac{30 \times 10^{-3}}{1 \times 10^{-7}} = 300,000 \text{ l/sec},$$

or, dividing by the perimeter,

$$S_{req} = \frac{300,000}{360 \times 12} = 70 \text{ l/sec-in.}$$

Somewhat more than this speed is required since only about 80% of the perimeter of the section will pump because of the space requirements for mechanical support. Thus a design target of ~90 to 100 l/sec-in. is set.

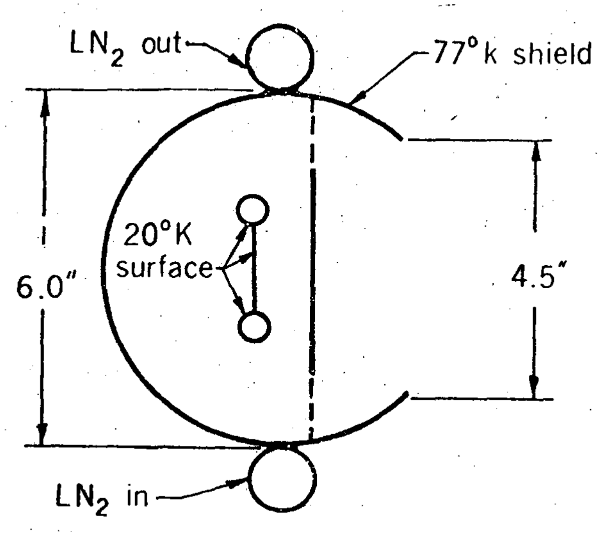

Fig. 4. Proposed cryopump cross section.

It became apparent early in the evaluation of proposed geometries that the expected thickness of the condensables on the 77°K shield would affect the emissivity of this surface. Measured emissivities for surfaces with water condensate are available in the literature. These data were applied to the anticipated thickness of condensates on the Bevatron proposals and average emissivities of 0.2 to 0.4 were computed for 2 to 3 days of operation at the fairly high load levels anticipated.

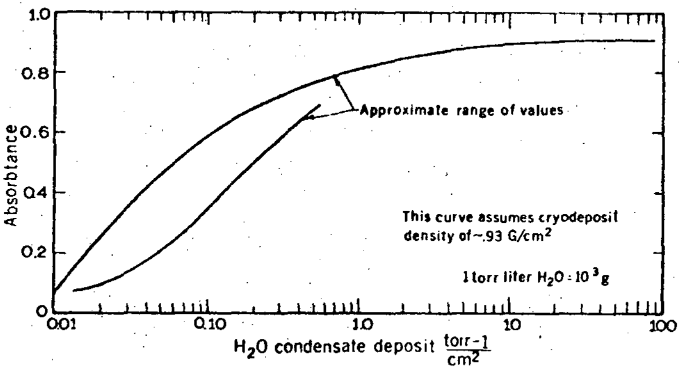

Fig. 5. Emissivity as a function of cryodeposit.

At these emissivities a system capable of air pumping speeds of 300,000 l/sec would consume 6 to 10 kW of LN_2 refrigeration power. Any plans to regenerate a low value for the emissivity of the LN_2 surface by heating it periodically must take into account the fact that hydrocarbons which make up a finite proportion of the condensable gas load cannot be expected to clean out under reasonable temperature cycles. Thus, it appears the high emissivity values must be lived with and designed for in our relatively "dirty" vacuum environment.

Monte Carlo and Figure of Merit

Because of the expected high operating costs due to LN_2 refrigeration for a given air pumping speed, it is clear that a pump geometry of minimum convex perimeter shield for a given air pumping speed is required. A two-dimensional Monte Carlo type program was devised so that accurate predictions could be quickly made for the capture probabilities and thus the pumping speeds of various geometries. This code would use Monte Carlo techniques to trace orbits on a statistically large enough sample of particles being emitted, reflected, lost, or absorbed in a two-dimensional array of straight lines and circles. The program would then take a census of the particles absorbed and lost, to determine the probability that a Maxwellian particle will be pumped (immediately or after several reflections) before it is lost. This code considers particles emitted from a source or reflected from a surface following Lambert's cosine rule (the probability of reflection or emission from a surface in a given direction is proportional to the cosine that that direction makes with the normal to that surface).

The code should closely approximate any free molecular flow system which can be considered as essentially two-dimensional in which the dimensions of the system are much smaller than the mean free path of any particle. The proposed Bevatron cryogenic pumping system, which is very long compared with its lateral dimensions and operates in a very high vacuum, can be realistically modeled with this code. A figure of merit is then computed for various pump cross sections:

$$m = \frac{\text{Air pumping speed}}{\text{Convex perimeter}} .$$

A sample result of the computation is included in Fig. 6. The maximum figure of merit for this particular geometry is:

$$m = \frac{98 \text{ l/sec}}{20.29 \text{ in.}} = 4.82 .$$

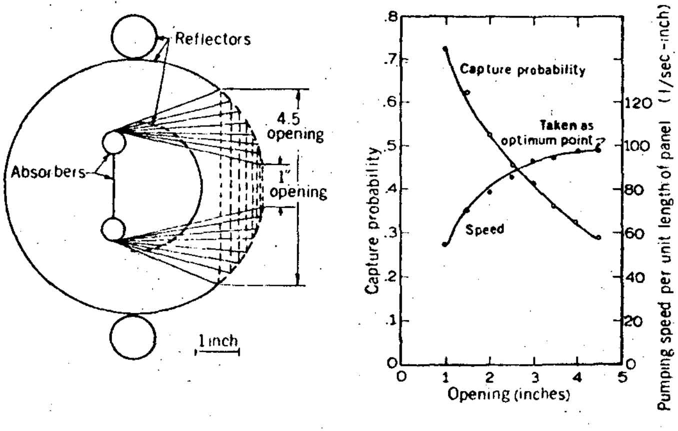

Fig. 6. Optimization of pumping speed for a given geometry.

It was very interesting to note that for a variety of geometries, once the pumping speed is maximized for a basic shield geometry, the figure of merit seemed to flatten out at approximately 4.8 l/sec-in.

Figure 2 shows the geometry currently being tested for use in the Bevatron. The computed parameters for the full-size model are reviewed on the following page.

Air pumping speed	335,000 l/sec
Condensables pumping speed	6,500,000 l/sec
Predicted emissivity after one week	0.44
Predicted LN_2 refrigeration load after one week	14.8 kW
Predicted 20°K refrigeration	25 W

A short test section is being tested and results of these tests should be available shortly.

Conclusion

It is felt that sufficient homework in the form of fairly reliable measurements and predictions based on essentially believable computations and data have been made and presented. The design at present is fairly well fixed. However, hardware as such has not been committed. Since a fairly wide latitude in the final geometry is allowable without severely compromising the design objectives, and since this latitude may encompass design alternatives which could greatly simplify some of the fabrication and installation problems which are, at present, apparent in the present design, we might conclude that the design could suffer further changes before final fabrication and installation.

Acknowledgments

This work owes a great deal to the design work of John Lax and the programming assistance of Carl Quong and Esther Schroeder. In addition, we would like to acknowledge the leadership in this project provided by Ken Lou and Dr. Hermann Grunder.

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

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