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University of California Ernest O. Lawrence Radiation Laboratory

THE 25-INCH LIQUID HYDROGEN BUBBLE CHAMBER

Berkeley, California

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UC-28 Particle
Accelerator and
High Voltage Machine
TID 4500 (29th Ed.)

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California
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D. U. Norgren, A. J. Shand, and R. D. Watt

May 25, 1964

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Contents

Abstract	v
I. Introduction	1
II. Chamber	
A. Body	1
B. Bellows	4
C. Inflatable Gasket and Glass Seals	9
D. Vacuum System	11
E. Refrigeration System	11
F. Refrigeration Operation	13
III. Expansion System	14
IV. Camera and Optics	19
V. Magnet	22
VI. Performance	24
Appendix	27
Footnotes and References	34

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ABSTRACT

A new 25-inch liquid hydrogen bubble chamber incorporates into its design many improvements and several unique features.

Unique to this chamber is a movable top window that serves both as the piston for the liquid-expansion system and as an optical condenser lens. The motion of this window is controlled by a single-convolution bellows welded into the chamber perimeter; use of such a bellows avoids frequency-response problems common with multiconvolution bellows. Due to the action of this top window, turbulence is virtually eliminated because no liquid either enters or leaves the chamber.

The aspherized condenser lens system is believed to be approximately five to ten times more efficient than any installed in earlier machines of this size. We count fewer ghost reflections, observe more uniform bubble tracks, and enjoy greater simplicity of operation than before. A scattering angle of 12° improves photographic uniformity in depth and avoids the need for individual light sources for each stereo lens.

This chamber combines a high degree of precision with a rapid operating cycle. At present the chamber can be operated twice during each Bevatron pulse, thus doubling the number of pictures taken. A conventional water-cooled magnet provides a vertical field of 18.5 to 22.8 kilogauss.

I. INTRODUCTION

During the last decade bubble chambers have been used as detectors of ionized particles produced by high-energy accelerators.¹ The 25-inch chamber is the fifth liquid hydrogen bubble chamber built and operated under the direction of Professor Luis W. Alvarez of the Lawrence Radiation Laboratory at Berkeley and has already taken over 700 000 physics pictures. A typical track photograph taken in this chamber is shown in Fig. 1.

Design studies for a 25-inch bubble chamber, begun in 1960 under the late J. D. Gow, incorporated the following specifications:

1. A precision chamber with sufficient sensitivity to permit bubble counting in liquid hydrogen and deuterium.
2. Incorporation of all the "best" features of photography.
3. Minimum turbulence; temperature gradients less than 0.1° K for low optical distortion due to variations in density and index of refraction.
4. A cycling or pulse frequency that could produce as many as five pictures (one every 90 milliseconds) for each accelerator pulse.
5. A stereo film format compatible with existing data-reduction equipment.
6. A magnet of about 18 000 gauss with coils to match several generators; the magnet assembly to be easily moved.
7. A design to allow for later conversion to liquid helium operation.

High-quality photography required through-lighting, hence two windows, and an expansion system that would minimize turbulence and dynamic heat load. To satisfy this requirement the chamber is expanded by moving the top glass relative to the lower glass. A single convolution bellows welded into the chamber perimeter permits this motion. Necessary bellows movement was determined by an investigation of the compressibility of liquid hydrogen and liquid deuterium; data were extrapolated below the saturated-vapor line.²

A cross section of the chamber and magnet are shown in Fig. 2.

Although the chamber is designed for liquid hydrogen, deuterium, or helium to be used in the tank, to date liquid hydrogen only has been used.

II. CHAMBER

A. Body

Materials for bubble chamber bodies must have certain properties such as:

1. Good strength and ductility as cryogenic temperatures.
2. Low (and permanent) magnetic permeability at 20° K.

ZN-4359

Fig. 1. Bubble chamber photograph.

MUB-2970

Fig. 2. Cross section of chamber and magnet.

3. No porosities.
4. Suitable fabrication and welding properties.
5. High electrical resistance at cryogenic temperatures.

To satisfy these conditions, the castings for the 25-inch chamber body and flanges were made from Kromarc-55, a relatively new (1960) austenitic stainless steel ($\approx 10\%$ manganese, chrome-nickel) developed by Westinghouse Electric Corporation. The selection of this material was based on the results of investigations made by Brookhaven National Laboratory for their 80-inch liquid hydrogen bubble chamber.³ As Kromarc-55 has excellent weldability, we have not had difficulty with any welds.

The chamber body was fabricated in two halves as shown in Fig. 3. More than twenty fittings were welded to the chamber body for various plumbing lines. A port for a thin window was cast into the chamber body and a 316 stainless steel sheet 0.040 in. thick was welded over the window opening. Three valves with indium seats were closely coupled to the chamber body to provide fill, vent, and purge operations. The completed chamber body with bellows and thin window were pressure tested to 250 psi internal pressure.

B. Bellows

The "omega" bellows were designed with a single convolution. This was done to avoid any frequency-response problems of multiconvolutions in which the bellows expands so rapidly that the first convolution only is deflected and overstressed. The bellows is made of two identical halves first welded to the chamber body and then welded together at the outer seam, as shown in Fig. 4.

Design was based on a bellows movement of 0.250 inch (0.125 inch on each side of the relaxed position and corresponding to a safety factor of ≈ 3), maximum operating pressure of 150 psi, and infinite fatigue life.⁴ A test fixture was built to cycle two prototypes of the bellows simultaneously under the design conditions of motion and pressure as the bellows designs were developed.⁵

The final bellows halves were fabricated from a low carbon (0.035%) 316-type stainless steel of 26 gage (0.0179 inch). The bellows were formed by a male die, after which the edges were machined and finally prepared by hand. Special welding fixtures were used for both the inside lip weld and the outside butt weld. The outside welds are always made last. Welding fixtures are shown on Figs. 5 and 6. The final welds were made in a universal-rotary-weld positioner using an "Airline" welding head equipped with rf controls. The weld was backed up with copper chill bars and completely shielded on both sides with argon gas.

The first bellows design called for a flanged-weld lip at the outer diameter. Two bellows, made from 305 stainless steel according to this design, were then tested satisfactorily in the test fixture (1 016 000 cycles) at 77° K. When the test was repeated at room temperature, the welds failed by

MUB-2971

Fig. 3. Cross section of chamber body.

MUB-2972

Fig. 4. Bellows detail.

ZN-4340

Fig. 5. Weld fixture for inside weld.

ZN-4341

Fig. 6. Weld fixture for butt weld.

fatigue at the outer weld because of a notch at the inside of this weld. The notch effect caused by the irregular hand weld was eliminated by changing the design to a butt weld at the outer diameter.

The first two butt-welded bellows were made from a 304 stainless steel, 0.019-inch thick. Leaks in the parent metal were due to radial cracks (three in one and one in the other) next to and running into the butt-weld metal. These cracks were repaired and the test continued. This pair of bellows was cycled more than 2 000 000 times at liquid nitrogen temperature; but when the test was repeated at ambient temperature, the repaired patches began to open after 500 000 cycles. This indicated that if the butt weld could be made without cracks, the bellows would have an infinite fatigue life at room temperature.

The bellows material was changed to a 316 stainless steel with low carbon content. A pair of these bellows, fabricated without any cracks or leaks, was then tested at room temperature for 3 300 000 cycles with no failure.⁶ This test satisfied the basic-design safety requirements.

The design was conservative for two reasons:

a. The final test was made at room temperature. The tensile and yield strength of stainless steel increases as the temperature decreases. For example, the tensile strength triples (from 80 000 psi to 240 000 psi); and since the endurance strength can be expressed as a function of the tensile strength ($S_{en} = 0.4 S_{ult}$), the fatigue strength is also tripled at low temperature.

b. The test conditions were severe. The bellows movement of 0.236 inch is more than three times the measured movement of 0.075 inch under actual operating conditions. The internal pressure on the bellows during the test was 150 psi, but actual operating pressure has been 85 psi with liquid hydrogen and 110 psi anticipated for deuterium operation.

C. Inflatable Gasket and Glass Seals

Inflatable gaskets have been used to make glass-to-metal seals on liquid hydrogen bubble chambers since 1958.^{1,7} Inflatable gaskets permit differential shrinkage between the glass and metal during the cooldown process. The final seal is made when the shrinkage is complete.

Two inflatable gaskets are necessary in the 25-inch chamber, as shown in Fig. 3. These gaskets are identical in design and construction, and are shown on Fig. 7. Each gasket assembly consists of a 304 stainless steel fabricated tube 0.012-inch thick welded to a set of 304 stainless steel rings. Forming techniques were similar to those used for the chamber bellows.

During cooldown the helium pressure in the gaskets is held at about 50 psi. The metal parts shrink about 0.060 inch more than the glass, and the gasket slips on the glass while the glass is held centered by the indium "centering" pads shown in Fig. 7. When the chamber is cooled to about 80° K, the gasket is "set" and the chamber is pressure tested up to 150 psi with helium gas. Helium pressure necessary to "set" the gasket is about 600 psi. Differential pumping on "cold pump-out" channels between two indium seals is used to monitor the performance of the gasket in order to insure the insulating vacuum.

MUB-2973

Fig. 7. Inflatable gasket and glass seal (P.O. means pump out).

D. Vacuum System

The chamber is thermally insulated by suspending it in a vacuum tank as shown in Fig. 2. Heat transfer is further reduced by the use of a copper shield cooled to liquid nitrogen (LN) temperature. Two independent vacuum systems consisting of an LN-trapped 4-inch oil-diffusion pump and a 15-cfm mechanical pump accomplish the vacuum pumping. One vacuum system pumps from the top and the other from the bottom of the vacuum tank. Although they are aided by the large cold surfaces of the LN shield, pumping is necessary when nitrogen, hydrogen, or helium leaks occur.

Nitrogen leakage can condense on the glass surfaces. However, the vapor pressure of frozen nitrogen (beta phase) is very close to the insulating vacuum pressure at the glass temperature, and in one instance the frozen nitrogen was pumped off.

The main vacuum tank was fabricated from 304 stainless steel. A beam window 0.040 inch thick on a reinforcing frame was welded to the tank. The upper end of the tank has a flanged larger diameter to accommodate the liquid-nitrogen-shield reservoir and the top-plate support-can chamber assembly. Camera windows and viewports are at the lower end of the tank.

E. Refrigeration System

Liquid hydrogen bubble chambers operate in a temperature range of 25 to 28° K. Refrigeration must be provided to cool components to this temperature, condense liquid hydrogen, and then maintain this temperature from heat transfer due to static and dynamic loads. Normal worldwide practice is to use a refrigerator that utilizes hydrogen as the working fluid in a liquid hydrogen bubble chamber.

The 25-inch chamber uses a hydrogen refrigerator operating in a closed Joule-Thompson (Linde) expansion cycle. The refrigerator has a capacity of 200 watts and uses a liquid nitrogen precool at 78° K. The refrigerator circuit is shown on Fig. 8.

Most of the components of this refrigeration circuit are adaptations of those used in the 15-inch bubble chamber refrigerator. The compressor and purifier were not changed and the refrigerator itself was only slightly modified by addition of an expansion valve. (The 15-inch bubble chamber refrigeration is described in Reference 8.) A somewhat major modification to the pneumatic-control circuit used on the refrigerator for the 15-in. chamber was necessary.

The refrigerator-control circuit for the 25-in. chamber is a modification of that used on the 72-inch bubble chamber refrigerator. A pair of valves, PCV 2 and PCV 3, control the mass flow and temperature of the refrigerant passing through the chamber heat exchanger. PCV 3, which is considered the temperature controller, is regulated through a pneumatic system controlled by a vapor-pressure thermometer immersed in the chamber liquid. PCV 2, which is considered the mass-flow controller, is regulated through a system controlled by two vapor-pressure thermometers monitoring the inlet and outlet vapor pressure of the refrigerant. In addition, a third

MUB-2974

Fig. 8. Flow diagram of refrigerator.

valve, PCV 1, stores available and excess refrigeration; PCV 1 will open as PCV 2 closes and the excess refrigeration in the form of liquid hydrogen is transferred to the liquid hydrogen pot.

The liquid hydrogen tank is an annular vessel located inside the main vacuum tank and above the chamber, as shown in Fig. 1. This vessel has three principal purposes:

1. Gas Holder Service

This vessel can be considered a "gas holder" or a source of hydrogen gas for the refrigeration system. The hydrogen tank normally vents to the refrigerator by way of the return-gas-transfer line.

2. Emergency Refrigeration

Liquid hydrogen in the hydrogen tank can be trickled through the chamber heat exchanger during those periods when the normal refrigeration is out of service. For prolonged periods without normal refrigeration, the tank can be filled with liquid hydrogen from dewars.

3. Precool Gas to Fill Chamber

Hydrogen gas to fill the chamber is precooled to liquid hydrogen temperature in a heat exchanger. This heat exchanger consists of multiple loops of copper tubing immersed in the liquid of the liquid hydrogen pot. A similar heat exchanger is built into the liquid nitrogen tank to precool the gas to LN temperature before it enters the liquid hydrogen heat exchanger.

The heat exchanger in the chamber consists of a loop of copper tubing soldered to a copper sheet. The copper sheet is rolled to a cylindrical shape but does not close the loop so that eddy-current forces are reduced should the magnetic field collapse rapidly. The heat exchanger is bolted to the bottom section of the chamber but extends to the highest part of the chamber.

Three transfer lines carry the refrigerant from the chamber heat exchanger and liquid hydrogen pot to the refrigerator. Each transfer line is a stainless steel tube inside a copper tube and is vacuum insulated. Conventional bayonet-type fittings are provided at the ends.

F. Refrigeration Operation

Refrigeration requirements vary during different periods of the experimental program. The refrigerator for the 25-inch chamber must handle the following demands:

- a. Cool down
- b. Hydrogen fill
- c. Static heat load
- d. Dynamic heat load
- e. Warm up.

Thermal stresses in the glass limit the rate of cool down to a limit for the top glass of about $4^{\circ}\text{K}/\text{hour}$.⁹ Fortunately the refrigerator matches this cool-down rate closely and cools the hydrogen gas down to liquid hydrogen temperature in about 70 hours.

Filling the chamber by condensing hydrogen gas takes about 10 hours. In normal operation this is the only period in which the capacity of the refrigerator is limited. For make-up fill periods the demand is generally low and within the refrigerator capacity.

The static heat load due to normal conduction and radiation and the dynamic heat load due to pulsing are very small. During the engineering run these low refrigeration requirements caused (a) cycling of the control system and (b) sticky control valves due to a combination of low flow rates and deposits of foreign materials around the valves and valve stems. These problems were overcome by putting heaters on the liquid hydrogen pot and regulating the amount of heat into the pot. As this has the effect of increasing the refrigeration demand, the increased flow rate keeps the transfer lines and plumbing cold and also "scrubs out" the control valves.

During the warm-up period the refrigerator circulates warm hydrogen gas to control the warm-up rate and prevent extreme temperature gradients on the glass.

III. EXPANSION SYSTEM

During the engineering run it was shown that direct chamber expansion by movement of the top glass satisfied the following criteria:

1. Low Turbulence in the Chamber Liquid

Turbulence in a bubble chamber causes "waviness" in the bubble tracks and must be minimized. The two major causes of turbulence are:

- a. Fluid movement due to expansion
- b. Fluid movement due to convective currents caused by thermal gradients.

Piston-type expansion systems have less liquid turbulence than vapor-expansion systems; the moving glass can be considered as the largest piston that can be designed for a chamber of a given volume. Also, heat loads are minimum in piston-type expansion systems because there is no mixing and thus weaker convective currents.

2. Uniform Sensitivity

Thermal gradients make the chamber vary in sensitivity throughout its volume, resulting in track photographs of varying density. The curved moving top glass initiates a small lateral motion in the liquid, which prevents the formation of radial thermal gradients.

3. Fast Expansion

Fast expansion is necessary to prevent spontaneous boiling. The compressed liquid hydrogen is a large energy source used to obtain fast expansion.

4. Fast Recompression

Fast recompression is desired to condense existing bubbles and reduce dynamic heat load on the liquid. Although a certain amount of energy is necessary to fully recompress the chamber, the work is done at room temperature.

5. Uniform Operation

Particle entry to the sensitized chamber must be timed to the light flash within 0.2 msec to produce uniform and reproducible bubble count and size. The mechanism for controlling the expansion system is accessible and is at room temperature; during the engineering run this feature was used in the development of an expansion system that would produce reproducible conditions.

The expansion system as finally evolved is shown on Fig. 9 and the expansion cycle is shown on Fig. 10. The motion is controlled with a hydraulic-pneumatic system having the following components:

1. Chamber

Energy for expansion is obtained from the compressed liquid hydrogen (about 70 psi) inside the chamber.

2. Drive Rods and Drive-Rod Pistons

The three drive rods connect the top glass to the hydraulic system. The support can acts in tension to restrain the lower chamber movement whereas the support rods act in compression.

3. Hydraulic System

The hydraulic system can be considered as a constant-volume system that transfers the displacement of the pressure multiplier to the displacement of the drive-rod pistons.

4. Pressure Multiplier and Cushion

The pressure multiplier and cushion consist of three pistons of different diameters driven by helium gas.

5. Helium-Gas System

By means of helium gas, the pressure multiplier is driven by a fast expansion-recompression system similar to systems used in other bubble chambers.

MUB-2975-A

Fig. 9. Expansion system.

MUB-2976

Fig. 10. Expansion cycle.

In operation the chamber moves about 0.075 inch, which measurement is estimated by squashing lead wires in the upper stop mechanism. This movement includes a small correction to compensate for the changes of deflection of (a) the support can in tension and (b) the drive rods in compression. When the chamber pressure drops 40 psi, the change of deflection is about 0.005 in, which means that the drive rod pistons move 0.005 inch more than the chamber.

A hydraulic pump supplies oil under pressure (≈ 2000 psig) to the expansion system. Oil leakage is compensated for between pulses by opening a valve that connects the hydraulic pump to the oil circuit. Three pipes of equal impedance transfer oil from the three drive-rod pistons to a manifold mounted on the pressure multiplier.

The pressure multiplier consists of three pistons on a single shaft. The upper piston (1-1/8-inch diameter) "sees" the oil. The middle piston (6-inch diameter) "sees" the helium from below and is vented to atmosphere from above. The third piston (2-inch diameter), the cushion, eliminates impact.

The cushion piston compresses gas on the downstroke. Both initial volume and pressure can be changed by adjustments. The gas cushion performs three functions:

1. Reduces impact on expansion. The gas "spring" prevents the piston from slamming into the valve body.
2. Provides adjustment for control of expansion pressure. The initial pressure and volume in the gas cushion contribute to the control of the movement of the piston and thus the chamber motion. Therefore the valley depth (expanded pressure) can be partially controlled by the gas-cushion pressure and volume.
3. Conserves some energy of expansion. Some of the work necessary to recompress the chamber is obtained from the compressed gas in the cushion.

The helium gas that drives the pressure multiplier operates in a closed system. Helium at 100 psi is normally applied to the helium piston and on expansion a quick-opening valve drops the pressure, the pressure-multiplier piston moves, and the chamber expands. The chamber is then recompressed by opening another quick-opening valve that reapplies helium pressure to the pressure-multiplier piston. The "expansion valve" and "recompression valve" are quick-opening rubber-boot-type valves designed to use Grove Flexflo components of 2-inch nominal size; these valves are driven by modified 3/4-inch, three-way Ross solenoid-actuated valves.

The mechanical expansion of the chamber bellows is physically limited by two safety devices (Fig. 9):

1. Support Legs

Four support legs bolted to the bottom half of the chamber body provide a fixed limit to the travel of the upper half of the chamber. These stops limit

the bellows movement to 0.250 inch and protect the chamber against failure of the drive rods. These stops are also necessary during chamber assembly.

2. Drive-Rod Stops

An adjustable pair of stops attached to the ends of the drive rods outside the vacuum also limit the chamber travel. The motion allowed by these stops is less than 0.110 inch and is within the travel limits permitted by the fixed stops with the final adjustment made after the cooldown has been completed. On the recompression stroke, the chamber is allowed to return to the lower drive-rod stops so that initial conditions for the next expansion are the same. On the expansion stroke the upper of these stops protects the chamber in case of gas-cushion failure.

IV. CAMERA AND OPTICS

The photographic system provides a large stereo angle, ample signal-to-noise ratio, and exceptional image quality in a relatively compact, economical package. As indicated in Fig. 11, a deeply aspherized condenser lens, efficient light absorbers, and large scatter angle are some of the key elements in the successful attainment of design objectives.

The generous stereo base (one half the object distance) makes possible superior ranging accuracy in the analysis of photographs and is believed to be the largest yet achieved for bubble chambers.

Axial placement of the compact light source permits interior storage of both hydrogen and nitrogen, simplifying plumbing and reducing heat losses. More importantly, it interferes less with the expansion system than would a more conventional layout based on the usually recommended 1.5 to 2.0° scatter angle (which would require from three to five separate lamps and light ports). Calculations show also that a more uniform intensity of bubble images results from the large (nominal 12°) scatter angle provided by this system. This is based on the fact that neither light intensity nor scatter angle remains constant as depth position in the chamber is varied. At the chosen angle the two variables are found to nearly cancel out.

Stray light is reduced by use of low-reflection coatings on interior optics and by installation of efficient saw-tooth light traps at the prime focus of both the condenser system and stereo objective lenses. So far we have been unable to provide suitable low-reflection coatings on the large elements; hence "flares" are visible in many of the photographs produced to date.

The camera (Fig. 12) is capable of rapid multipulse operation. The design objective was to photograph five expansions in one Bevatron pulse lasting approximately 1/3 second. At present the Bevatron can give two beam bursts during one accelerator pulse, doubling the rate previously accepted. A unique system incorporating dual differential film drive capstans, special Geneva drive unit, and internally sensed, programmed electric clutch, can advance the film in less than 60 msec. The film is accelerated (and decelerated) at 17 G's to obtain this performance. High-speed vacuum platens capable of cycling in 10 milliseconds were developed for the camera.

MUB-3380

Fig. 11. Optics arrangement.

ZN-4363

Fig. 12. Stereo camera.

For the first time in the history of the LRL bubble chamber program, difficulty was experienced during preliminary grinding operations on the precision window. Two blanks were cracked beyond salvage. It is interesting that although the annealed blanks were from separate pourings and were being processed at different plants, circumstances surrounding the two unfortunate occurrences were similar, to wit:

Type of machine:	Blanchard
Mounting:	Laid on turntable with eight radial clamps positioned against periphery and held by magnetic lines of force.
Time:	Shortly after starting up machine the morning after having worked on the blank the previous afternoon.
Temperature:	Coolant water several degrees colder than glass, due to evaporative heat loss. The temperature difference increased as grinding continued, resulting in increased tensile stresses in surface of glass.

Corrective action consists of maintaining the "coolant" temperature at the same level as the glass blank.

V. MAGNET

The magnet arrangement has a circular-core design as shown in Fig. 13. All of the eight leg slabs are removable and can be located in different positions so that the particle beam can enter the chamber from various angles.

There are two coils of six pancakes each, both of which are water cooled and designed to match several generators ranging in capacity from 350 to 4000 kilowatts.¹⁰ The magnet is cooling limited at a water pressure of ≈ 500 psig.¹¹ The two-layer pancakes are bifilar (2 in hand) wound, which allows a better space factor for the same differential water pressure. Bifilar winding permits a vigorous dc high-voltage test, as one conductor can be held at ground potential and the other at test voltage. Other magnet parameters are listed in the Appendix.

These coil pancakes are wound with the water inlet at the outside of one layer and the water outlet at the outside of the other layer. The coil conductors are thermally coupled together by the epoxy encapsulation and transfer heat from one conductor to the other. The two coil layers simulate a heat exchanger. If the conductors are tightly coupled thermally, the heat-exchanger effect can be so strong that the conductor and water temperatures near the center of the coil can be higher than the outlet water temperature and lead to coil failure. This effect was suggested by J. W. Mark at Argonne and H. Brechna at Stanford Linear Accelerator and is discussed in Reference 12. The heat-exchange effect is not significant in these coils.

MUB-2977

Fig. 13. Magnet plan view.

The magnetization curve of magnetic field B_z in the axial direction is shown on Fig. 14.¹³ The radial profile of fringe field along the center line of the entrance beam (B_z vs radius) is shown on Fig. 15.

The magnet is supported on a cylindrical structure that also houses the camera. In order to adjust the vertical placement of the chamber, the magnet can be raised vertically by a set of four commercial hydraulic cylinders to allow addition of shims. The four cylinders are equally spaced and have individual commercial caterpillar-type rollers attached. The magnet is moved by towing it very slowly over preplaced steel plates ($\approx 1/2$ inch) to protect the concrete floor.

VI. PERFORMANCE

Of the 700 000 pictures taken to date, 265 000 have been taken with the chamber operating in the double-pulse mode. For each pulse of the Bevatron, two pulses of beam, separated by 300 msec, are sent to the chamber. There is some difference in expansion depth between the two pulses because of leaky vent valves allowing plumes of gas to enter the chamber on the first pulse. The bubbles of gas are not fully compressed by the time the second pulse arrives; hence, a shallower expansion.

Each expansion cycle is controlled separately to enable similar conditions to exist on each pulse. The timing of each pulse of beam with respect to the expansion depth is adjusted to give the same number of bubbles per cm, and each light delay is adjusted to give the same bubble size. The number and size of bubbles is specified by the physicist in charge of the experiment. A typical specification is 12 bubbles/cm in the chamber and 20- μ bubble size on the film.

The Bevatron is currently limited to two beam pulses per Bevatron pulse because there are only two "rapid beam ejectors" (RBE). The chamber is limited to two pulses because of the leaky vent valves, which will be replaced by a better design in the future. With the addition of another RBE at the Bevatron and the replacement of the leaky vent valves, the chamber should be able to take three beam pulses per Bevatron pulse.

MUB-3381

Fig. 14. Magnetization curve of magnetic field in axial direction.

MUB-3382

Fig. 15. Radial profile of fringe field along center line of entrance beam.

APPENDIX

Summary of Specifications

Working Fluid

Type	Hydrogen or deuterium
Volume (liters)	85
Normal Operating Temperature (°K)	27 hydrogen 31.5 deuterium
Operating Pressure (psig)	65 to 35 hydrogen 95 to 45 deuterium

Chamber Assembly

Chamber Body

Nominal i. d. (in.)	24
Maximum o. d. (in.)	30.75
Body height (in.)	14.75
Liquid height (in.)	10 at center 13 at outer radius
Material	Kromarc-55
Weight (lb)	491
Test pressure (psi)	250

Chamber Flanges

Material	Kromarc-55
Weight, top (lb)	330
Weight, bottom (lb)	400

Inflatable Gasket

Material	304 stainless steel
Material for seal	Indium, 99.999% pure
Normal accommodation (in.)	0.035
Maximum accommodation (in.)	0.070

Vacuum Tank

Volume (ft ³)	58
Material	304 stainless steel
Test Pressure, Maximum (psig)	150

LN Shield

Material	OFHC copper
Weight (lb)	1400
LN Reservoir Capacity (liters)	80
LN Consumption (liters/hour)	≈ 7

LN Tank

Material	304 stainless steel
Weight (lb)	230
LN Capacity (liters)	≈ 50

LH Tank

Material	304 stainless steel
Weight (lb)	265
LH Capacity (liters)	≈ 65

Expansion System

Type	Piston
Pulse Rate (ppm)	20
Chamber Pressure	
Before pulse (psig)	65
Expanded (psig)	≈ 35
Expansion-Recompression Time (msec)	30
Expansion-System Driving Fluid	Helium
Expansion Valve	Modified 2-inch Grove Flexflo

Recompression Compressor Type	Brunner two stage	
Rating (hp)	10	
Discharge pressure (psig)	150	
<u>Refrigeration System</u>		
Liquefier		
Refrigerant	Two-phase hydrogen	
Inlet pressure (psig)	1800	
Expansion valve	Joule-Thompson	
Refrigerator capacity (W) at 26° K	200	
Compressor (scfm)	35	
Compressor type	Norwalk four-stage horizontal	
Compressor rating (hp)	30	
<u>Vacuum System</u>		
Mechanical Pumps (Kinney)		
Dewar and LH transfer lines (1)	KC-2	
Main vacuum (2)	KC-15	
House vacuum and pumpouts (4)	KC-15	
Camera vacuum (1)	KC-5	
Diffusion Pumps		
Dewar (1)	2 inch	
Main insulating vacuum (2)	4 inch, HS4-750	
<u>Magnet</u>		
Type	Direct current	
Orientation of Field	Vertical	
Effect Gap (in.)*	44.8	48.8
Field at Center of Chamber (G)	18 500	22 800

Weight of Steel (tons)*	40	40
Weight of Copper (lb)*	20 700	20 700
Ampere-turns	1.68×10^6	2.25×10^6
Number of Turns	624	624
Direct Current (A)	2700	3600
Voltage (V)	375	507
Power (MW)	1.03	1.80
Coil Cooling		
Flow rate (gpm)	250	250
Temperature rise ($^{\circ}\text{C}$)	19.5	18.0
Coolant		Low-conductivity water

Optics

Illumination System

Light source	Five Edgerton FX-51 xenon flashlamps in parallel array, ≈ 300 watt-sec. in 200 μsec
Diffuser	Opal glass disk, 5-in. diameter adjacent to lamp array
Filter	Yellow (Kodak K-2), 5-inch diameter Useful aperture = 24.6 in. Focal length = 20.4 in. (dry) Focal length = 22.6 in. (in LH)
Condenser set (2 elements)	Max relative aperture = $f/0.83$ (LH) Operating numerical aperture = $f/0.38$ (LH)
First element	Sphero-aspheric borosilicate crown Diameter = 26.4 in. Maximum thickness = 5.5 in.
Second element	Plano-convex borosilicate crown Diameter = 27.0 in. Thickness = 4.7 in.

* calculated values

Absorber	Sawtooth light trap (black anodized aluminum)
Stereo Geometry	
Lens focusing distance (in.)	58
Lens separation (in.)	19.8 (normal) 28 (diagonal)
	Lenses occupy three corners of a square
Stereo angles	
To precision fiducials	29° (maximum)
To beam in hydrogen	18° (minimum)
Pressure Windows	
Lampwell port	Borosilicate crown, grade C, 1 in. thick
Chamber upper window	This is second condenser element made of grade C borosilicate crown
Chamber precision window	4 1/4 in. thick grade A borosilicate crown, 27 in. diameter
	Maximum deviation of normal rays not to exceed 20 sec of arc
Bottom ports (1.75 in. thick quartz)	
Precision stereo (3)	Schlieren quality quartz Maximum deviation not to exceed 5 sec of arc
Polaroid camera (1 only)	Quartz, grade B
TV camera	Quartz, grade C
Side port	
Viewing window	Pyrex
Camera	
Lens complement (6)	Schneider lenses
Chamber stereo (3 lenses)	Matched Super Angulon f/32, F = 90 mm

Chamber Polaroid (1 only)	Componon, F = 135 mm
Data input, Polaroid (1 only)	Componon, F = 150 mm
Data input, 46-mm filmstrip (1 only)	Componon, F = 80 mm
Platens	
Type	Vacuum, with integral solenoid-operated valves
Response time	3 milliseconds to full vacuum.
Auxillary equipment	Margin-marking lamps Vacuum alarm switch
Wind Capstan	
Minimum-design wind time	68 msec
Minimum-design repetition rate	88 msec
Prime mover	1/6 hp capacitor-type ac motor
Supply Magazine	
Capacity	4000 ft film
Duration	8 hours (single pulsing) 2 hours (maximum rep rate)
Data	Integral with camera
<u>History</u>	
Design Started	23 March 1960
First Operation with Liquid Hydrogen	November 1963
First Physics Operation	28 February 1964

Cost

General	\$ 34 000
Magnet	145 000
Chamber and Expansion System	183 000
Vacuum and Refrigeration	115 000
Optics and Camera	124 000
Electronics	150 000
TOTAL	<u>\$ 751 000</u>

FOOTNOTES AND REFERENCES

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

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