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NUCLEAR PHYSICS BOARD OF THE SCIENCE RESEARCH COUNCIL

Rutherford High Energy Laboratory

Completion of Helium Bubble Chamber Project

Note prepared by the Chairman of the Management Committee

Submitted by T.G. Pickavance

1. The Governing Board of the National Institute for Research in Nuclear Science approved the design study for a large Helium Bubble Chamber at their meeting on 20th June, 1960. In July, 1961, the Governing Board accepted a recommendation from the Physics Committee that the construction of the chamber should proceed and Treasury approval was obtained for the project on 11th November, 1961.

2. The work involved has been carried out as a joint project by a team of physicists and engineers from both the University of Oxford's Department of Nuclear Physics and the Rutherford Laboratory.

3. A Management Committee was formed in May, 1962, to consider all major aspects of the design, construction and testing programme and to exercise control over the finances of the project. This Committee consisted of members from the University of Oxford, the Rutherford Laboratory, together with bubble chamber specialists from other universities. The Management Committee was strongly supported by a joint Technical Committee and also by the Finance and Estimates Sections of the Rutherford Laboratory. At a final meeting of the Committee held on 27th April, 1967, outstanding technical and financial matters were considered and it was agreed that with the successful operation of the chamber the work of the Committee had been brought to a satisfactory conclusion.

4. The original Treasury approval for the project was £416,000, comprising £324,000 for plant, spares and contingency, together with £92,000 to cover the salaries, stores and travel for the University of Oxford staff engaged on the project. During the course of the project Treasury approval was obtained for an increased plant estimate of £55,000 resulting from the cost of the refrigerator being higher than originally estimated. It also became necessary to obtain Treasury approval for an additional £26,000 for a year's extension to the University Agreement. The total approved estimate was therefore £497,000. The final cost under all headings is expected to reach £457,000. Further details of this estimate are given in Appendix I.

5. The chamber first operated early in February, 1967, and again in March, 1967 when both a beam from Nimrod and the power supply for the magnet were available, satisfactory quality of performance being demonstrated. Preparations are in hand for the chamber to be used for a high energy physics experiment commencing next June. A technical description of the chamber is given in Appendix II.

6. Although it will not be certain until the first high energy experiment on the chamber is completed, it is not anticipated that any modifications to the installation outside the normal field of operational development will prove to be necessary.

7. It is therefore brought to the attention of the Nuclear Physics Board that the Helium Bubble Chamber has been successfully completed and that the chamber is now ready for use in the Nimrod experimental programme.

FINAL REPORT ON PROJECT COSTS

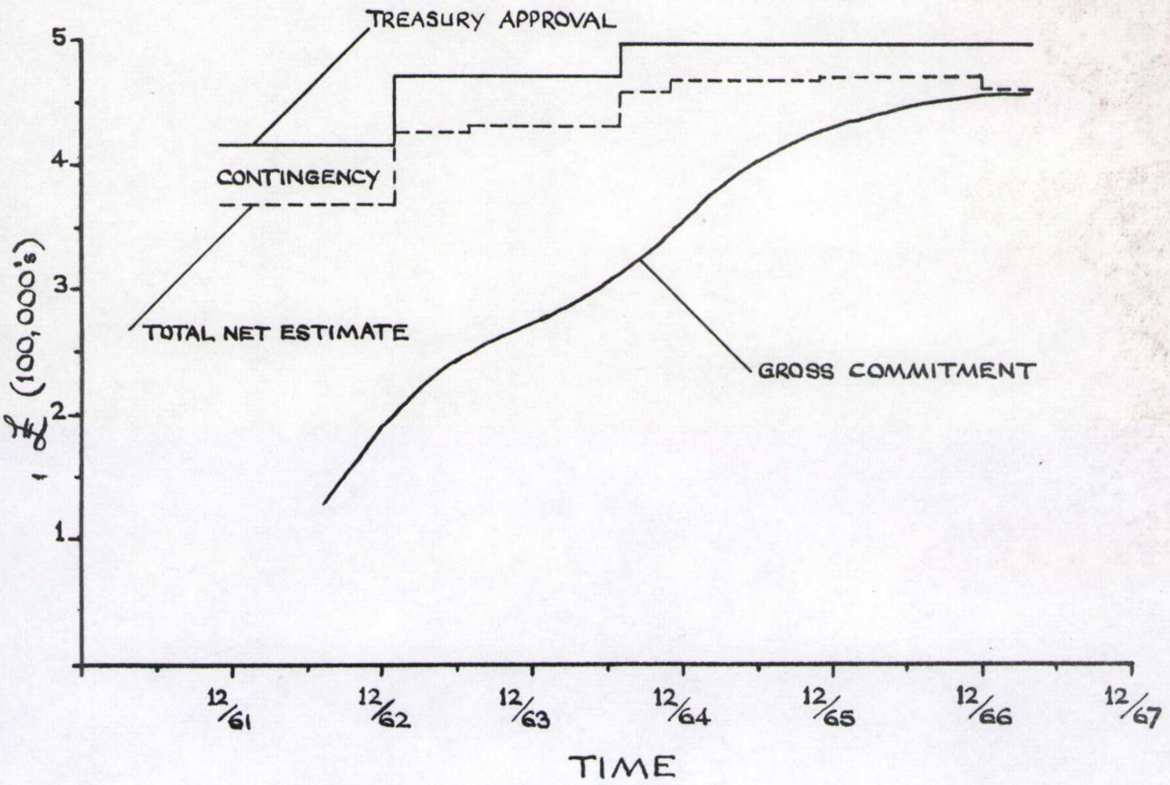
Treasury Approval of £416,000 was given for the Helium Bubble Chamber in November, 1961. It was increased just over a year later to £471,000 when the results of the tenders for the refrigerator were available. One further increase to £497,000 was given in July, 1964, when it could be seen that the R & D estimate was inadequate. These changes, together with the variations in the estimates and the amount of gross commitment are shown graphically in Appendix IA. The Treasury Approval included a sum of £16,500 for re-orientation of the chamber to the horizontal field mode. The Technical Committee have recommended, and the Management Committee agreed, that this would not now be needed.

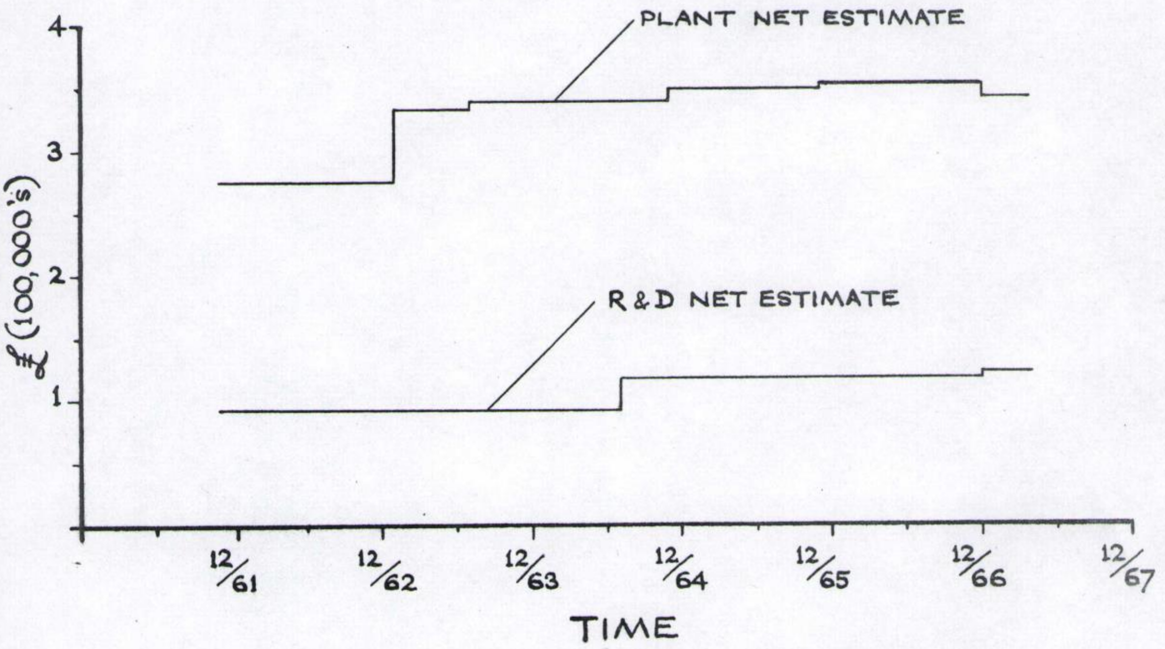
The position at the completion of the project is:-

Treasury Approval		£497,000
Final cost of R & D (including University costs)	£121,618	
Current Plant commitment is £335,011 and small variations on finalisation are not expected to give a final plant cost in excess of	£335,382	
∴ Estimated Final Total Project Cost =		£457,000

which is:- 10% (or 2% p.a.) above the first approval, but 8% below the final approval.

The total expenditure to 31.3.66 was	£422,000
Estimated expenditure during 1966/7 was	£ 32,000
Estimated expenditure during 1967/8 is	£ 3,000
	£457,000


TREASURY APPROVAL
CONTINGENCY
TOTAL NET ESTIMATE
GROSS COMMITMENT
£ (100,000's)
5
4
3
2
1
12/61
12/62
12/63
12/64
12/65
12/66
12/67
TIME


PLANT NET ESTIMATE
R & D NET ESTIMATE
£ (100,000's)
4
3
2
1
12/61
12/62
12/63
12/64
12/65
12/66
12/67
TIME

THE HELIUM BUBBLE CHAMBER

Introduction

The Oxford University - Rutherford Laboratory Helium Bubble Chamber is designed to operate in a vertical magnetic field in order to simplify the problem of transporting a low momentum beam of charged particles into the chamber.

A direct dark field illumination system was adopted and large horizontal windows are provided at the top and bottom of the chamber. Although the choice of horizontal windows led to some criticism about the possibility of large vertical temperature gradients being established near the top of the chamber, preliminary tests indicate that this is not a serious problem with a suitably designed refrigeration system.

The work of constructing, commissioning and maintaining was carried out in an annex to the main experimental hall of the Science Research Council's 7 GeV proton synchrotron, Nimrod.

The bubble chamber assembly, including the vacuum system, the sub-ambient parts of the refrigerator and all instruments and controls other than electrical, was designed so that it could if necessary be moved as a single unit to different positions in the main experimental hall. The refrigerator compressors, gas storage and the pre-purification system and other fixed units are installed in a plant room adjacent to the annex.

The following sections are intended as a brief description of the major components of the Helium Bubble Chamber. The major contractors are listed in Appendix IIA and some photographs of the bubble chamber are shown in Appendix IIB.

Magnet

The magnet weight is approximately 70 tons. It produces a field of 22 kilogauss at the centre for a current of 8×10^3 amperes. The dissipation at full field is 3.6 megawatts. Provision is made for bringing slow particles through the fringe field of the magnet at angles up to 90° to the long axis of the chamber by having a number of removable sections in the return yoke of the magnet. The coils are divided into 2 sets, 6 double pancakes above the beam line and 6 double pancakes below. Each double pancake has 42 turns and the halves of a double pancake are cooled in parallel; that is, the water flows in from the outside of the coils and returns to the cooling tower from manifolds on the inside of the coils.

Vacuum Tank and Vacuum System

The vacuum tank is a stainless steel cylindrical vessel 4 feet in diameter and is inserted into the hole in the magnet yoke. The top of the vacuum tank is covered by a large 3 ins. thick stainless steel rectangular plate from which the chamber and its radiation shields are suspended. A high vacuum is maintained in the system by two independent, 10^3 litres a second pumping systems. The design of the pumping system has ensured that very little back-streaming of vapours is experienced. The pressure in the vacuum tank during running is 3 to 8×10^{-7} torr.

Chamber Assembly

The top plate of the vacuum vessel forms the support for the chamber and its radiation shields. This top plate is bolted to the main suspension frame of the system which runs horizontally across and is clamped to the top of the magnet yoke and from which the main vacuum system and the controls and instrumentation are suspended. The subsidiary vacuum systems, the oil pump for the actuator which controls the expansion system and various connections to auxiliary supplies are also supported from the main frame; thus the bubble chamber assembly can be removed from the magnet with a minimum of pipe disconnections. The chamber proper is surrounded by a vacuum-tight shield at about 4°K which contains helium gas at about 60 torr pressure. This shield is surrounded by a radiation shield which is separately refrigerated at about 80°K. The radiation shields are also suspended by stainless steel supports from brackets underneath the top plate. The vacuum tank, the shields and the top plate have ports holding small glass windows so that the chamber can be illuminated and photographs of the particle tracks can be taken. The chamber itself is a casting made in an austenitic stainless steel, similar to Kromarc 55. The inside dimensions of the chamber are approximately 17.25 ins. by 20.75 ins. by 33.25 ins., the walls being about 2 ins. thick to ensure rigidity. The bottom window of the chamber through which the light passes is 2 ins. thick. The top window, which is of higher quality, as the photographs are taken through it, is about 3 ins. thick with a one inch deep step so that the top turn of the refrigerating coils lies above the lower face of the top window. A 4 ins. diameter entrance window for the particle beam is provided at one end of the chamber, the thickness of this window being about 0.375 ins. of stainless steel. To provide a uniform expansion, one vertical side of the chamber is allowed to move outwards increasing the volume of the chamber by up to 1%. This wall is connected to the chamber body proper by a vacuum-tight flexible stainless steel rectangular bellows.

Window Seals and Gaskets

0.125 ins. diameter indium wire is used to seal the main windows to the chamber body in the usual way. The seals are made at about 80°K by pressurising rectangular inflatable gaskets to about 400 lbs. per square inch (thus pressing the windows against the indium seals). As the chamber operates at low pressures it has been possible to place the inflatable gaskets outside the windows without having pressures in the gaskets greater than 500 p.s.i., thus reducing the irregular surfaces where parasitic boiling of the liquid inside the chamber might take place.

Refrigeration and Heat Losses

The specification of the refrigerator required 500 watts at 80°K and a gross 80 watts at 3°K. The net heat available for refrigerating the chamber at 3°K after taking away the losses in connections and transfer lines is about 60 watts. Having to work between 4°K and 3°K results in there being very small temperature differences available for refrigerating the liquid in the chamber and a large surface area was required for the heat removal from the chamber. This is achieved by circulating 2 phase mixture of helium through copper pipes actually in the body of the liquid. The outside of the chamber is in thermal contact with cooled helium gas to help keep the chamber body temperature uniform. The 4°K shields are surrounded by the 80°K radiation shields which are refrigerated by the flow of helium gas at 80°K from the refrigerator. The process fluid, in this case helium, is transferred from the refrigerator to the bubble chamber by five vacuum insulated and radiation shielded lines; a flow and return at 80°K, a flow and return at 3-4°K and a separate filling line which is strapped at intervals to one of the 3°K lines. The measured heat losses from the outer shield are between 400 and 500 watts. The static heat load of the 4°K system is about 35 watts with less than 20% increase when expanding with a 60 msec long pulse at one expansion each two seconds.

Expansion System

In order to keep the dynamic heat losses low it was decided to use a liquid rather than a vapour expansion system since the heating in a liquid cycle is very much less than in a vapour cycle. Considerable amount of research and development work was put into the design of the rectangular omega bellows which make the vacuum seal between moving side wall of the chamber and the chamber itself. The final design had a circular convolution of radius 1 inch, the rectangular dimensions of the whole bellows being 16 ins. by 30 ins. with the corners rounded to a 5 ins. radius. The material used to construct the bellows convolutions is 18/8 stainless steel.

As the maximum stresses occur round the corners at points away from the external perimeter, the bellows convolutions could be made in 2 halves welded together round the perimeter. Each half is a pressing from a uniform sheet of stainless steel 12 thou. of an inch thick. One half is welded to the bellows flange and the other half to the moving side wall of the chamber. The two halves of the convolution are finally joined by a weld round their outside edge.

As it was required to remove the chamber and vacuum tank from the magnet with the minimum amount of dismantling, the control of the movement of the side wall has to be turned through a right angle so that it could come out through the top plate of the chamber. A triangular bell-crank design was used for this and it was necessary to develop bearings which could be run at 3-4^{o} absolute. No lubrication of course could be used at these low temperatures and the design consisted of roller bearings in a molydisulphide impregnated nylon cage. There is only a small rocking movement and the test bearings were subjected to many million reversals under full load conditions at low temperatures before the design was accepted. The movement of the side wall is controlled by a hydraulic oil actuator at room temperature. The force of about 3 tons is transmitted from room temperature to 3^{o}K by a stainless steel shaft in a concentric return thrust tube. The bell-crank and bridge system are connected to the chamber body by flexible links to minimise the stress on the chamber supports during expansion. The movement of the actuator is measured by a proximity meter which compares the position of the piston in the actuator with the predetermined electrical pulse. The difference signal actuates Moog fast acting valves which control the flow of oil to the actuator. The movement of the side wall is designed to be 0.25 inch; however in operation it was found that a stroke of 0.125 to 0.1875 inch is all that is needed.

Illumination

The refractive index of liquid helium is about 1.025; therefore at small angles the amount of light refracted from a vapour bubble in a forward direction is greater than for the corresponding angle with hydrogen. It was decided to adopt a 4^{o} scattering angle, which corresponds to 2^{o} in hydrogen, and to provide a separate light source for each camera. In the geometry adopted, these light sources are focussed 4 ins. laterally from the camera lens. The chamber is small enough to enable one set of condenser lenses to cover the full area of the chamber. The main condenser system has two components, the upper lens being double convex, with the top surface aspheric and the lower lens planoconvex. To reduce the amount of scattered light the light sources are imaged onto a stop inside the vacuum tank. As the beam height of Nimrod is 75 ins. from the ground, the complete condenser system could not be accommodated in one vertical line and each illumination channel has to have a bend of 90^{o}. Light enters through windows in the sides of the vacuum tank and shields and is reflected by mirrors to fill the main condenser system. The main condenser lenses and the precondenser system are suspended from the bottom of the chamber body. The light sources which are outside the vacuum tank are spiral flash tubes about 1 inch in diameter and the measured images of these in the plane of the camera lenses are less than 3 ins. in diameter. Each light source can dissipate about 50 joules per flash at a repetition rate of 1 flash each 2 seconds. A double layer anti-reflection coating has been evaporated onto the surfaces of the condenser lenses and windows of the chamber and the light ports.

Photographic Arrangements

In order to make the best use of the helium in the chamber it was decided to arrange the cameras so that as much as possible of the volume is seen by at least 2 cameras. The four cameras are therefore placed approximately at the corners of the bubble chamber. It was agreed to use unperforated 35 mm track chamber film, and cameras holding 1000 feet of film have been designed. The image of the bottom window of the chamber occupies a format of about 31 mm by 62 mm on the film. To reduce the distortion due to non-flatness of the film it is proposed to use a telecentric camera lens designed by Dr. Welford of Imperial College. As it was realised that the development and manufacture of this lens would take considerable time, the first photographic system has been set up with Schneider Symmar lenses and the system has been arranged so that these lenses can be replaced by the telecentric lenses when they are available.

Helium Refrigerator

The refrigerator is required to cool the bubble chamber to $3^{\circ}K$ and the radiation shield to $80^{\circ}K$. The refrigerator provides at the chamber more than 500 watts of refrigeration at $80^{\circ}K$ and about 60 watts at $3^{\circ}K$ rising to 200 watts at $4^{\circ}K$; the temperature being controlled to $\pm$ $0.05^{\circ}K$. All the low temperature part of the refrigerator is supported from the bubble chamber magnet and moves with it on the main suspension frame, while the compressors, gas storage cylinders and prepurification system are located in the plant room. The refrigerator has been operated continuously for more than 30 days without maintenance. The refrigeration is obtained by two stages of turbo-expanders with helium gas lubricated bearings; each stage has two turbines, either of which can be removed and serviced without stopping the refrigerator.

The upper turbines expand the helium from 10 atmospheres at $70^{\circ}K$ to 1.5 atmospheres at $50^{\circ}K$ while the lower turbines expand the helium from 10 atmospheres at $18^{\circ}K$ to 1.5 atmospheres at $13^{\circ}K$. The final cooling is by a Joule-Thomson valve from $7^{\circ}K$ to $4.5^{\circ}K$, the liquid collecting in a 200 litre capacity liquid helium reservoir. To refrigerate the chamber, liquid from the refrigerator is flashed to the pressure appropriate to the required temperature and the two phase mixture is sucked through the chamber cooling loops by a sub-atmospheric pressure compressor (one of the complications of the helium bubble chamber has been the need for refrigeration pressures to be below atmospheric). A massive system of very efficient gas-to-gas heat exchangers is necessary to obtain the required refrigeration. These are plate-fin heat exchangers and can easily handle the three and four gas streams with temperature differences of $1^{\circ}K$ or less.

Pressure and Temperature Control

The thermal expansion of liquid helium is about 15% $^{\circ}K^{-1}$. As the chamber system has essentially a fixed volume it is necessary to provide a system to take care of the change in liquid volume due to small changes in temperature ($\sim 0.1^{\circ}K$) so a reservoir has been provided. This is a cylinder 4 ins. in diameter and 42 ins. high, a temperature gradient being maintained between the top and bottom of the reservoir so that liquid helium surface finds its level at the point where the helium vapour pressure is equal to the working pressure of the chamber. For small changes in liquid temperature the liquid level falls or rises and then slowly returns to the equilibrium position. A pipe of high dynamic impedance connects the reservoir to the chamber and a pipe from the top of the reservoir is connected to a continuous flow pressure control system at ambient temperature. Make-up helium to the chamber is supplied by a small continuous flow of cooled helium to the lower end of the expansion reservoir. Temperature control of the chamber is by adjusting the pressure of the two phase mixture passing through the chamber refrigerating coils.

Controls and Display

In designing the layout of the diagnostic and control units for the bubble chamber the following points were considered:-

(1) The time constants associated with the low temperature parts of the bubble chamber are long ($\sim 10^3$ secs) so a system that provides rapid control is to be avoided.

(2) Adequate space should be available round diagnostic and display units so that there is easy access for maintaining components, diagnosing faults and remedying them.

(3) As far as possible control units for different major components have been kept separate so that individual units can be situated in the most convenient positions.

(4) The physicist or engineer in charge should be able to assess the state of the chamber and its associated equipment and be able to make decisions without being hampered by having to do routine checking or having to adjust the controls.

The operation of the chamber is monitored from a console which can be moved, if required, to a position remote from the diagnostic and operational units. The console has visual indications of the readiness of the system and has audible and visual warnings of the malfunctioning of the chamber components. Action to cure a fault is taken at the appropriate diagnostic unit. As far as possible the units have been designed to "fail safe". For some major items such as the expansion turbines, main vacuum system and the proximity meter, complete duplicate systems have been provided.

D. Roaf

LIST OF MAJOR CONTRACTORS

In addition to the work done by the Engineering Division of the Rutherford Laboratory, the Department of Applied Optics at Imperial College, London, and the Nuclear Physics Laboratories at Oxford, major items of equipment were supplied by the following firms:-

UNITED KINGDOM FIRMS

Aluminium Pressure Vessels Ltd.	Lower Helium Shield.
British Oxygen Company	Helium refrigerator and associated equipment.
Broom & Wade Ltd.	Vacuum pump for Helium refrigerator.
Chesterfield Tube Company	Helium storage cylinders.
Dowty Rotal Ltd.	Hydraulic actuator for side wall of chamber.
Edgar Allen Ltd.	Magnet yoke.
G.E. Taylor Ltd.	Demineralised cooling water circuit.
J & P Engineering Company	Camera magazines.
Lintott Engineering Company	Final machining of chamber body.
Marston Excelsior Ltd.	Heat exchangers for Helium refrigerator.
Marconi Company	Closed circuit T.V. equipment.
Morfax Ltd.	Inflatable gaskets & bellows for side wall.
Optical Surfaces Ltd.	Telecentric Camera lenses.
Optical Works (Ealing) Ltd.	Chamber illumination windows.
Robert Jenkins Ltd.	Main vacuum vessel.
Sterling Cable Company	D.C. distribution system.
Vickers Armstrong (Engineers) Ltd.	Top helium shield.
Worthington-Simpson Ltd.	Booster pump unit.
Wantage Engineering Company	Main frames and constructional work.

OVERSEAS FIRMS

Corblin (France)	Diaphragm compressor.
Fisba Optical Precision Instruments (Switzerland)	High quality small windows.
G. Fischer (Switzerland)	Casting for chamber body.
Galileo (Italy)	Main optical window, condenser lenses and vacuum system.
Jos Schneider (Germany)	Camera lenses.
Linde (Germany)	Main compressor.
Oerlikon (Switzerland)	Magnet and its transport system.
Schott (Germany)	Cast glass blanks for windows and condenser lenses.

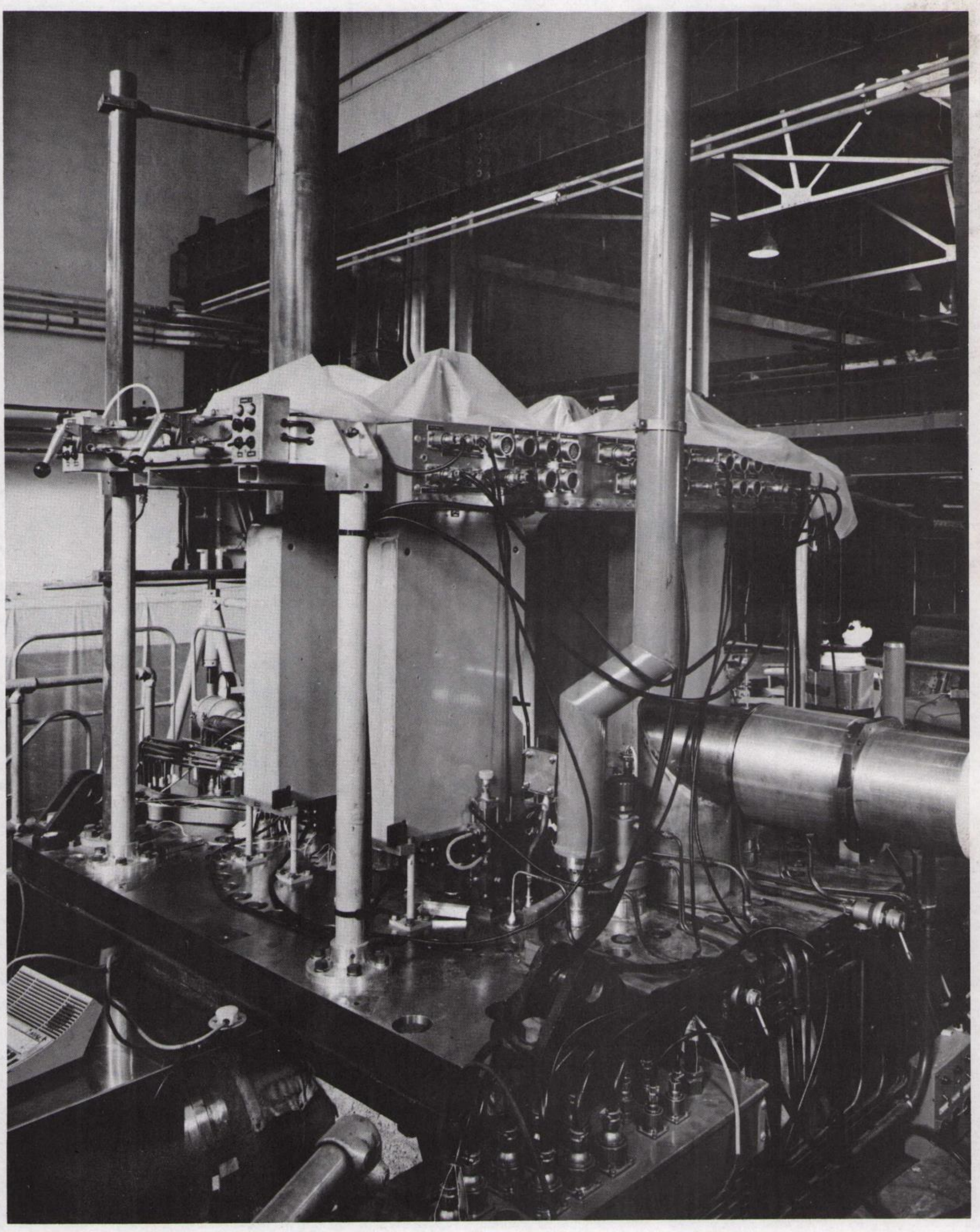


Figure I: View of Chamber top-plate and cameras.

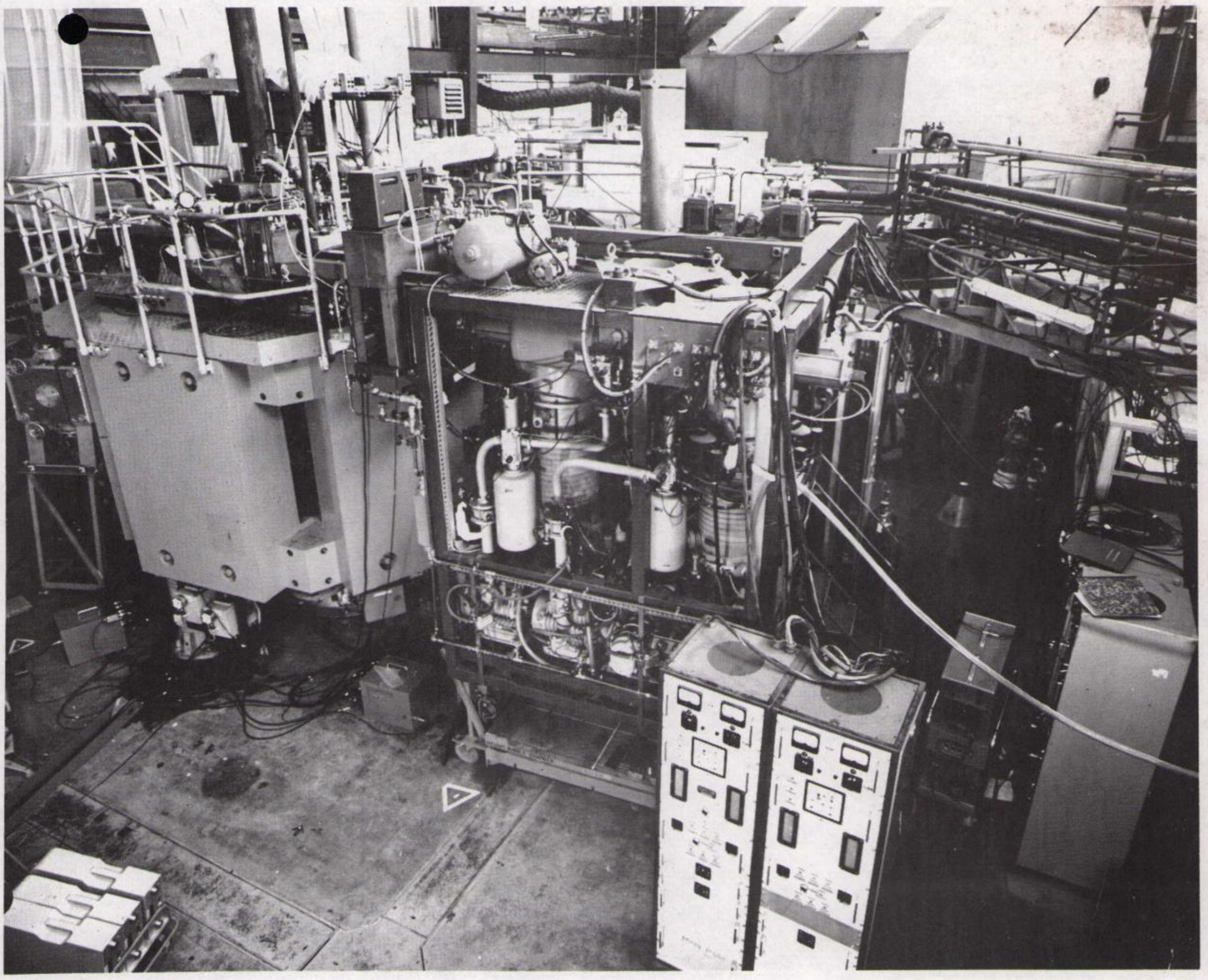


Figure II: Overall view of the Helium Bubble Chamber showing the magnet and Vacuum systems.

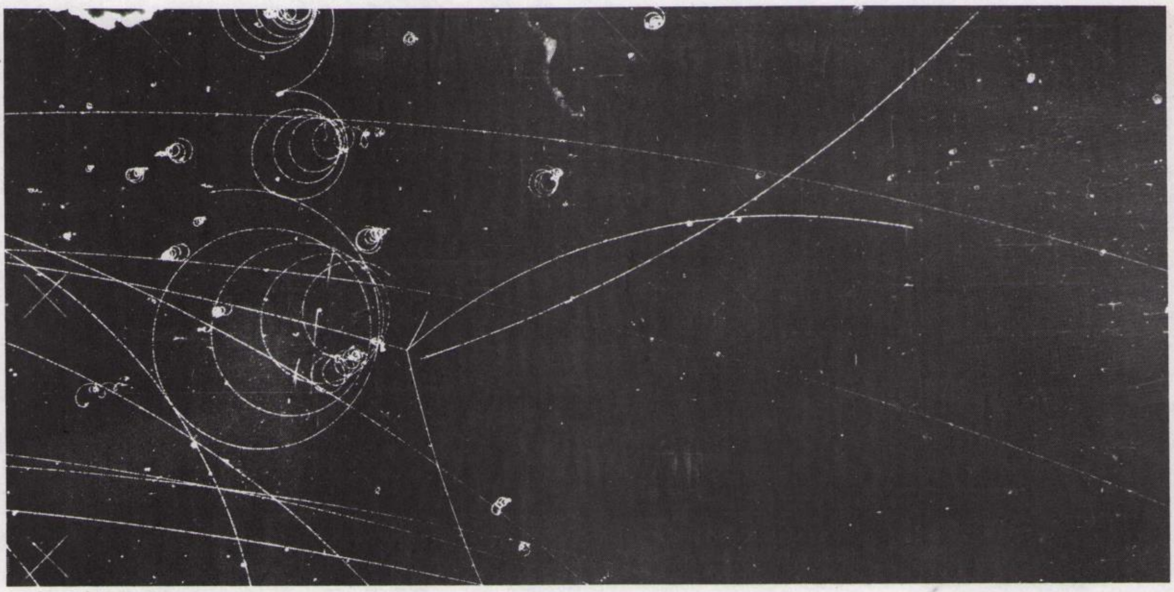


Figure III: Interactions produced during a technical run with a 1.5 GeV/c π-meson test beam.