HIGH ENERGY PHYSICS

With The

BROOKHAVEN 80" HYDROGEN BUBBLE CHAMBER

Foreword

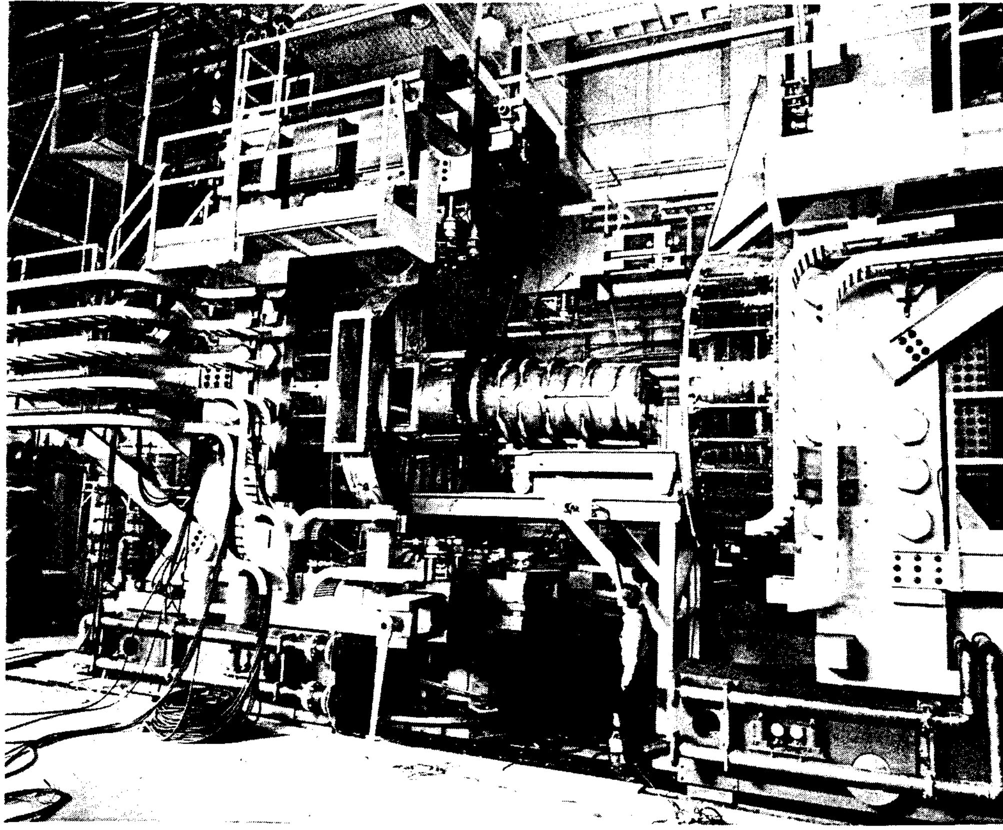
Members of Brookhaven National Laboratory's Bubble Chamber Group have prepared this booklet for those interested in the Laboratory's research efforts in high energy physics with bubble chambers. In this field, the funds and manpower required for design, construction, and operation of a large bubble chamber are exceeded only by those for the accelerator itself, which produces the high energy particles required for experiments. The chamber serves as a target and particle detector and provides data sufficient for many research teams at many universities and laboratories in the United States and in other countries. This booklet, then, describes some of the technical and scientific work of a large number of people during a period of several years.

Many illustrations have been included for clarity and to achieve some degree of completeness. An attempt has been made not only to describe a particular bubble chamber, but also to explain how the bubble chamber technique fits into an experiment's sequence: accelerator, beam, chamber, data processing, and interpretation.

We should like to thank Brookhaven's Photography and Graphic Arts Division for their many contributions and for their patience and cooperation.

R.P. Shutt
For the BNL Bubble Chamber Group
July 22, 1966

Installation of the safety chamber in front of the chamber body. The safety chamber shields the liquid in the bubble chamber from thermal radiation; equally important, it would catch glass fragments and liquid hydrogen if the large glass window should ever break.



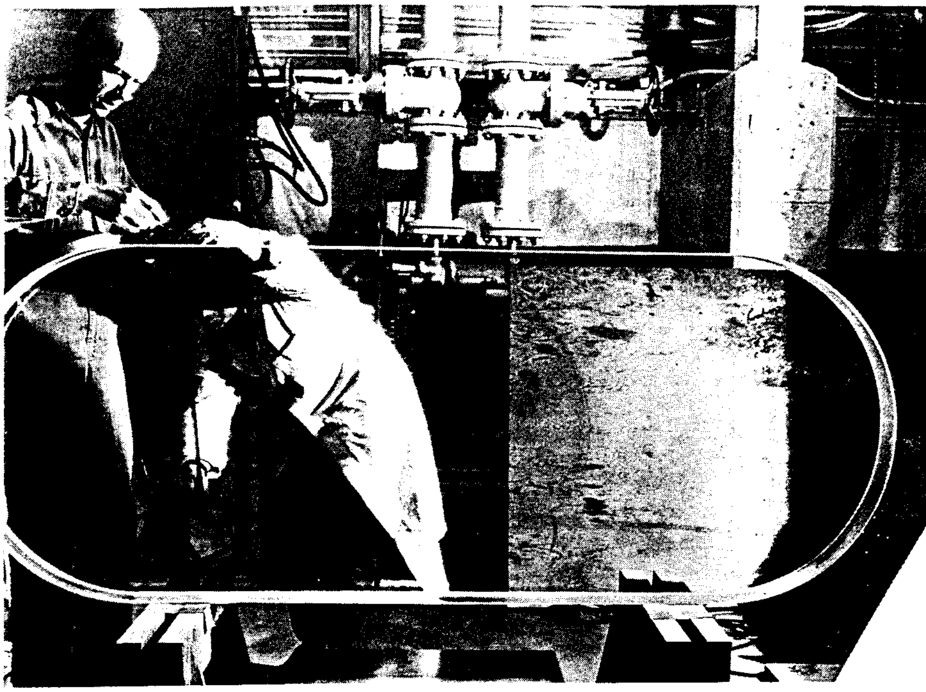
Particle Beams for the Bubble Chamber

The source of incident particles for the 80-inch bubble chamber is the AGS complex, but selection of the desired particles and directing them into the chamber require considerable manipulation. The AGS produces per pulse over 10^{12} protons with energies up to 33 BeV, far too many to be accommodated in the chamber, where only 10 to 20 particles per pulse are usually admitted. Also, the most exciting results may not necessarily be obtained from protons colliding with protons in the chamber. Other particles may be more interesting even if they have lower energies. Therefore, the AGS proton beam is allowed to hit a solid target and thus produce a very large number of secondary particles, which fly off in all directions and with many different velocities. This creates a situation as chaotic as in the case of cosmic radiation except that the particles come toward the chamber from one source only, and their intensity is high enough that there is a good chance of screening out a sufficient number of the desired particles.

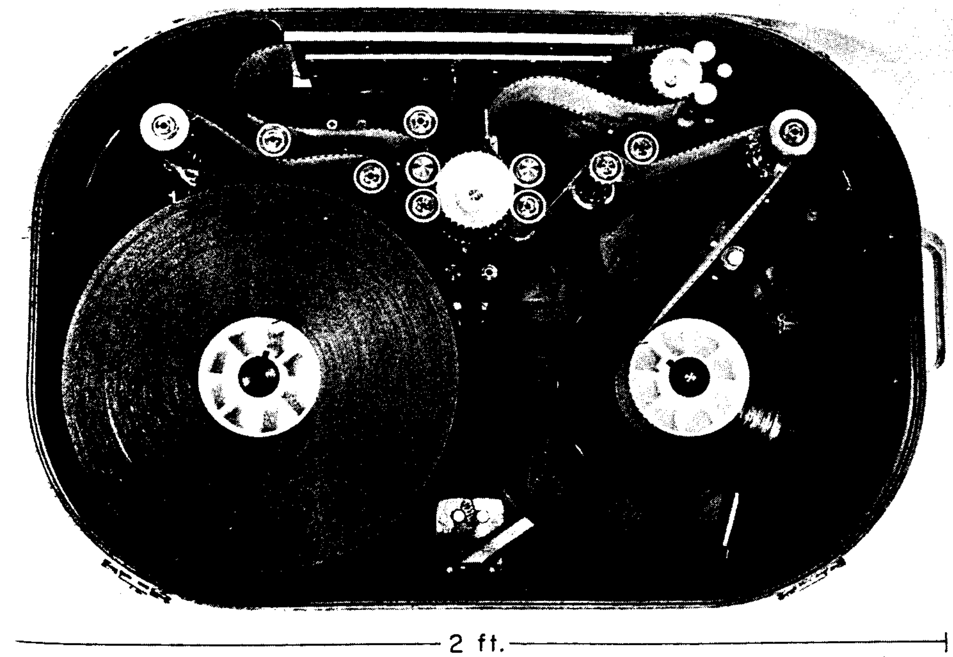
bubble chamber body and within the magnet, is necessarily of complicated shape and intricate design.

The chamber body is kept at a constant low temperature by means of a hydrogen refrigerator which circulates hydrogen at a controlled low temperature through passages drilled along the chamber walls. The hydrogen refrigerator is a closed recirculating system in which refrigeration is produced by expansion of high-pressure hydrogen gas through orifices (Linde cycle). The hydrogen gas is compressed to 2000 psi by two 5-stage compressors that together require 250 horsepower. Then, after passing through a series of room-temperature and low-temperature purifiers and heat exchangers, it is expanded through variable orifices, which serve to control the pressure in the refrigeration circuits and by this means to control the temperature. The still cold hydrogen returning from the chamber refrigeration circuits passes through heat exchangers to precool the incoming hydrogen gas and thus improve the efficiency of the refrigeration cycle. The refrigerator has sufficient capacity to carry off 2500 watts of heat at $-412°F$.

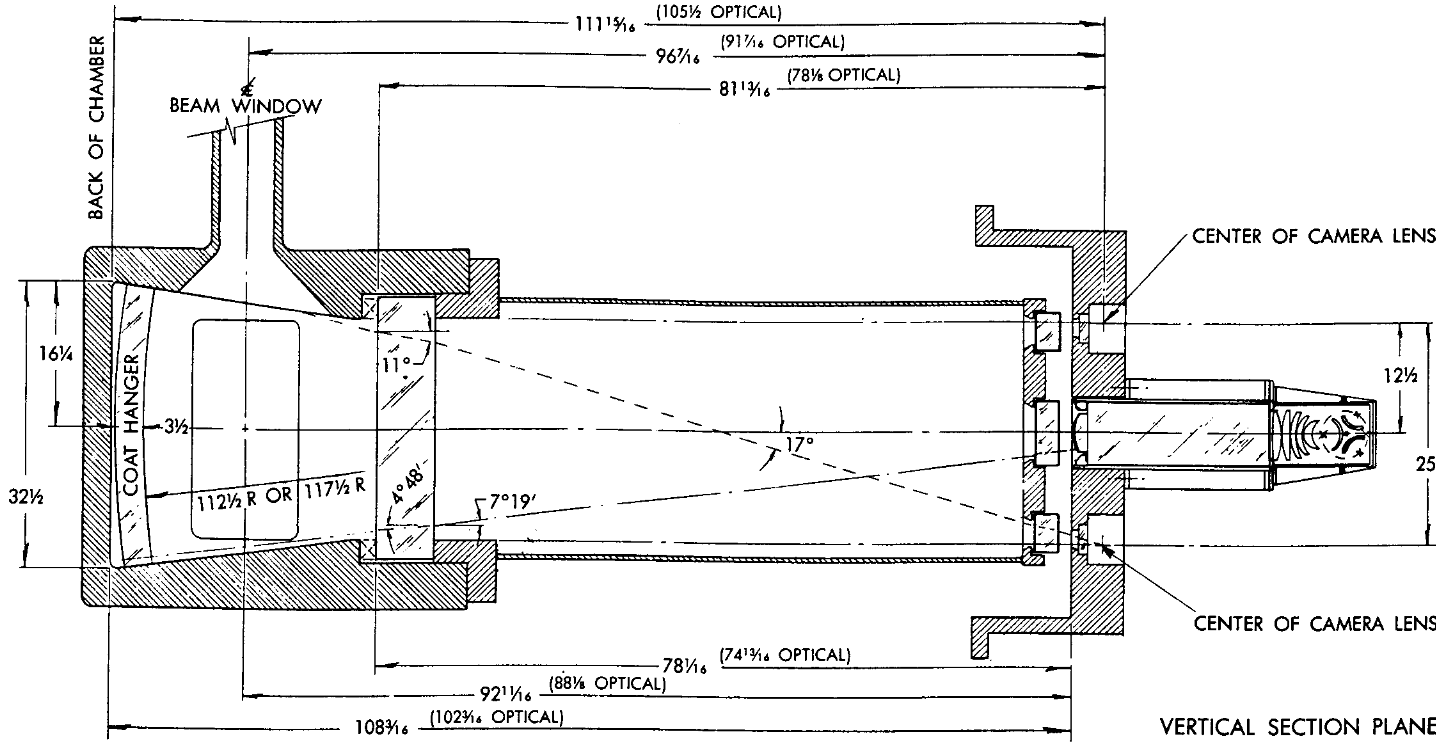
All the controls for the expansion system, the refrigerator and compressors, the high vacuum system, the magnet, the pulsed lights, the cameras, and many other smaller systems are located in a central control room, where the status of every unit in the machine is displayed on instrument panels. (More than 140 miles of wire were used for the connections.) Temperatures, pressures, flow rates, magnet current, vacua, valve positions, and number of pictures taken are among the items of information indicated. The control room is also the center of a communication network for the entire complex. An on-line electronic computer automatically logs statistics and data vital to effective operation of the chamber. Audible and visual alarms are actuated immediately if a malfunction occurs anywhere in the chamber complex. A crash button enables the operator to empty the chamber rapidly in case of emergency. The chamber contents are dumped either through a vent line and stack into the atmosphere or into a 28-foot-diameter safety sphere that can safely store all the hydrogen or deuterium gas.



The glass window for the 80-inch bubble chamber. It weighs 1500 pounds and is 6½ inches thick, 81 inches long, and 30 inches high. For added strength this glass is tempered by a heating and subsequent rapid cooling procedure. Since pictures are taken through this window, it may deviate from flatness by only a few light wavelengths per inch. The optical quality of the glass must be excellent, free of bubbles, inclusions, or other sources of distortion.



Loaded camera magazine. Film from the spool at the left is guided through mechanical drives past the opening at the top, where it is exposed to the bubble images provided by a photographic lens. The mechanism must advance ≈ 6 inches of 70-mm film every second. The film must be very flat in order to avoid distortion; it is therefore pulled back against a metal plate by a vacuum.



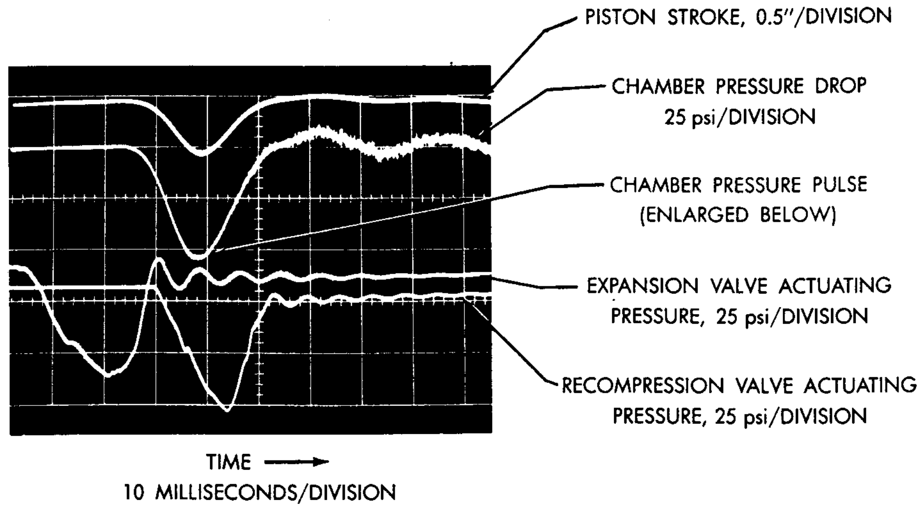
Schematic showing the light source assembly (right) consisting of a xenon-filled quartz tube and an optical condenser system to focus the light through an opening in the vacuum chamber. The light then travels toward the "coat hangers" (left), where it is reflected back toward the source. Some of the light is scattered by the bubbles toward the camera windows, where an image of the bubble can then be produced.

Installing the coat hangers inside the 80-inch chamber body. This must be done with very high precision to insure uniform chamber illumination. The plastic coat hangers are shaped almost like cylindrical lenses focusing light on a silvered reflecting surface on their back side. This system eliminates the mirror images of bubbles which would be seen if, for instance, a large open mirror were installed to reflect the light back toward the source.

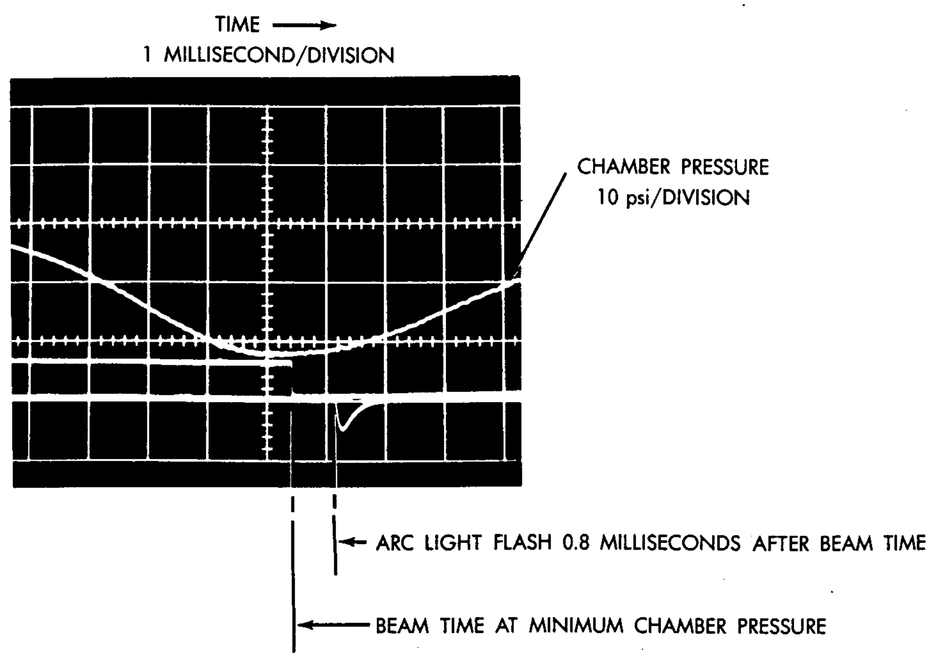
A light source located 8 feet in front of the chamber is flashed approximately 1/1000 of a second after the particles have passed through the chamber. The light is reflected back from the rear of the chamber toward the light source, but some of it is scattered by the bubbles toward 4 ports for cameras spaced around the light source and causes the images of the bubbles to be formed on 70-millimeter photographic film. The light passes through several glass windows, among them a glass plate 6½ inches thick, 81 inches long, and 30 inches high that weighs 1500 pounds and is precision-ground to optical tolerances. A magnetic field of about 20,000 gauss, acting in a horizontal direction parallel to the optical axis, deflects the charged particles in the vertical direction and produces curvature of the tracks. The magnet coils consist of 31 tons of copper bus bar, about 2 by 2 inches in cross section, with a central hole for cooling water, wound in a race-track shape to fit around the chamber. A current of 16,000 amperes, supplied to the coils through a series of transformers and a large group of rectifiers, is produced by a potential difference of 250 volts and results in a power consumption of 4 megawatts. The copper coils alone would not produce the required 20,000-gauss field; they are aided by an iron yoke which facilitates the return of the magnetic flux. This iron yoke, including a heavy undercarriage, weighs about 400 tons and is strong enough to act as the support structure for the entire apparatus. The undercarriage permits translation of the magnet assembly on rails and allows the magnet structure to be opened for easy access to the chamber body and associated equipment. The magnet structure is propelled by a 100-ton-capacity hydraulic pusher, and it can be elevated by four 200-ton-capacity synchronized jacks and rotated on a large roller bearing.

The hydrogen chamber is insulated by several hundred layers of thin aluminized plastic sheets (Mylar®) to shield it from the large amount of heat radiation due to the large temperature difference between the inside and the outside. Since heat conduction and convection must also be drastically reduced, the chamber is placed inside another chamber that is evacuated to a high degree of vacuum (like a thermos bottle). This vacuum chamber, which must fit around the entire

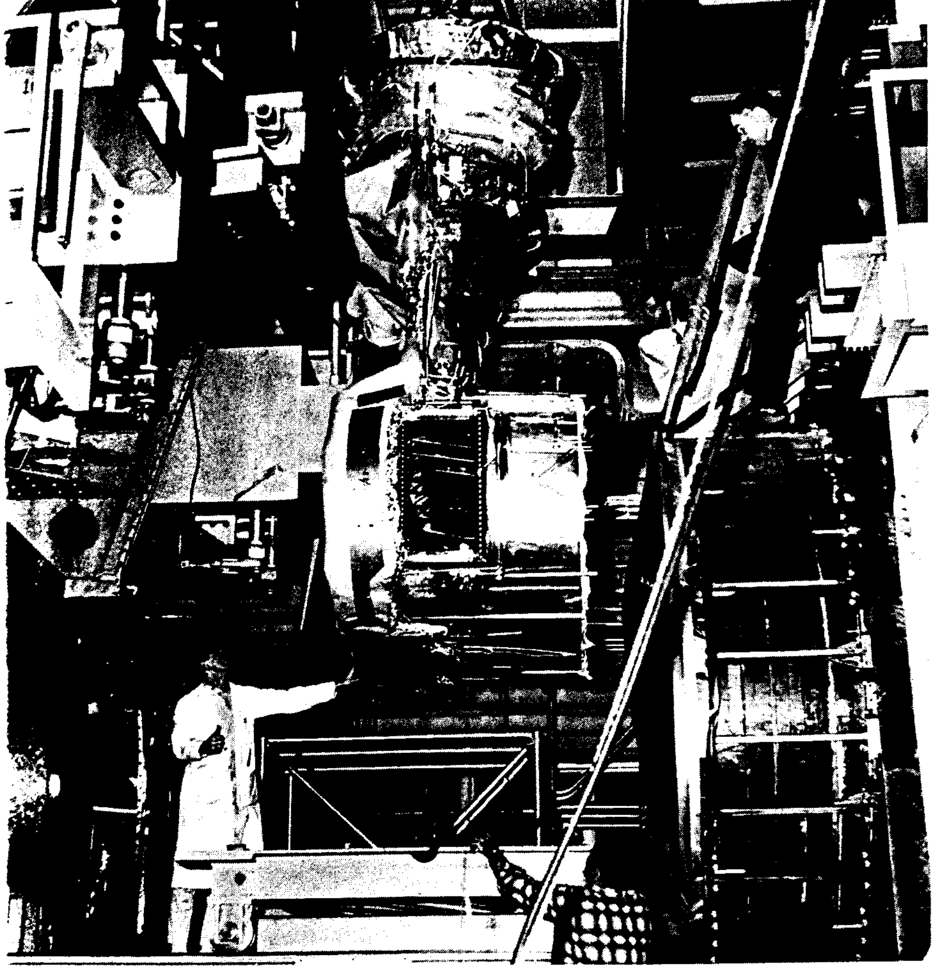
EXPANSION SYSTEM PULSE



ENLARGED PORTION OF CHAMBER PRESSURE PULSE



Oscilloscope photographs of the expansion system pulse showing the time functions of the piston motion, chamber pressure, and actuating valves. The lower figure shows the chamber pressure near its minimum and the beam timing and light delay on an expanded time scale.



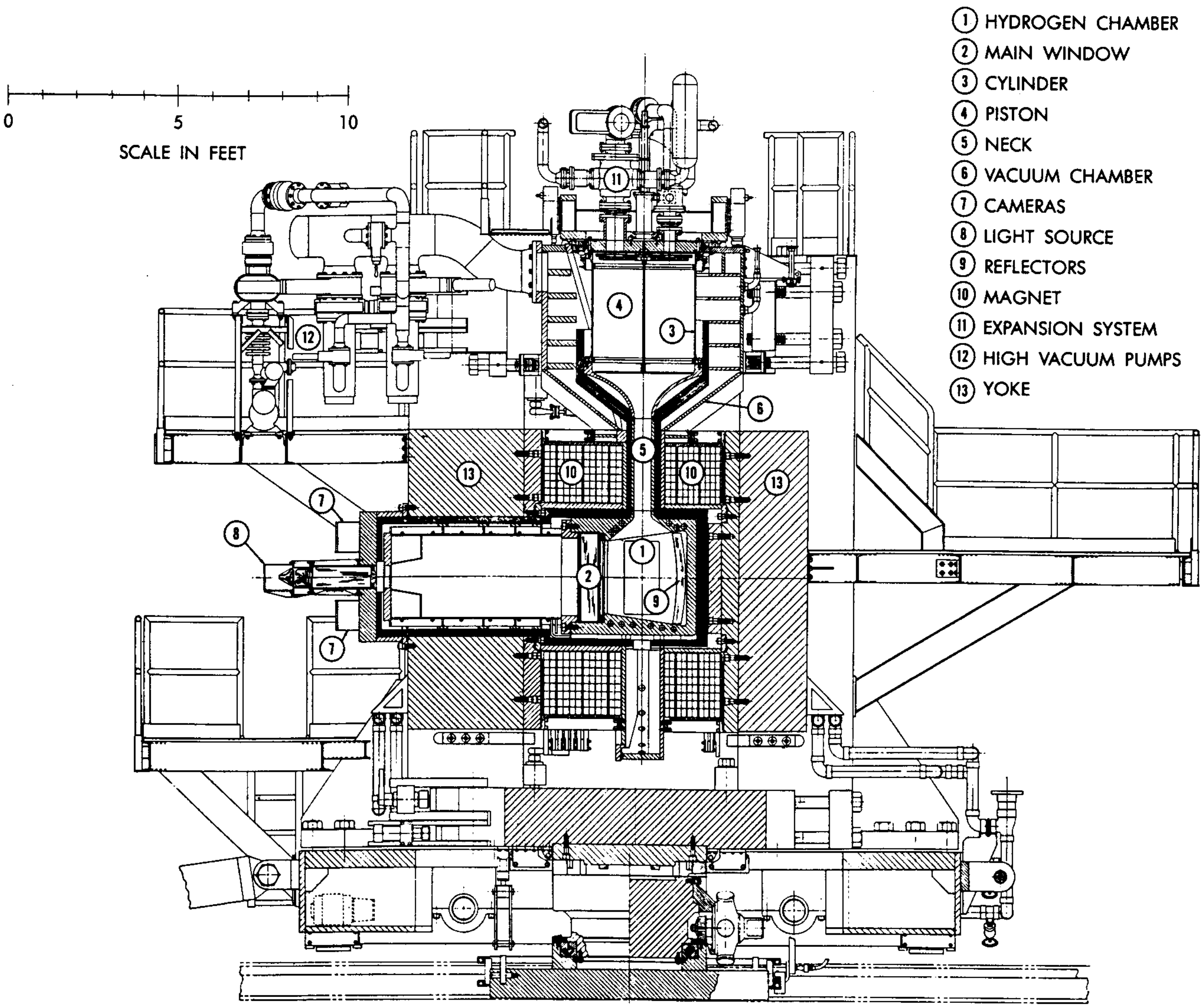
Body of the 80-inch bubble chamber being lowered onto a fixture for insertion in the stationary section of the vacuum chamber, visible at the left. The bottom part of the neck through which the chamber is expanded can be seen through the still-open beam window. A portion of the multiple-layer insulation is already mounted on the chamber.

Thirty-six-inch-diameter piston for the Brookhaven 80-inch liquid hydrogen bubble chamber. Inconel sheet metal 0.003 inches thick has been corrugated and brazed together with 36-inch-diameter face sheets to form a cellular structure. Also brazed to the assembly are the rings at top and bottom carrying high-density polyethylene seal-and-wear rings. A rod at the top of the 250-pound piston leads to a pneumatic control for positioning it between expansions.

The chamber body containing the liquid hydrogen is made of a special stainless steel (Kromarc 55) and weighs 11 tons. It is about 27 inches wide and 80 inches long with rounded ends, and 26 inches deep. Visible to the stereoscopic cameras are 240 gallons (900 liters) of liquid hydrogen. At its top, the chamber has a wide neck leading to a 36-inch-diameter cylinder containing a piston 32 inches high. The piston is constructed of Inconel sheet metal brazed together in a hexagonal cell (honeycomb) structure, which makes it very strong yet light (250 pounds) for its large size. The bottom of the piston, being in contact with the liquid hydrogen, is kept at about $-412°F$. There is a temperature gradient along the height of the piston, since its top surface is surrounded by gaseous hydrogen at room temperature; the insulating properties of the honeycomb structure minimize heat losses. The equilibrium pressure above the piston is controlled at the normal chamber pressure, 80 psia. Expansion of the liquid is accomplished by rapidly venting the hydrogen gas above the piston by means of high-capacity, fast-acting valves. This produces a pressure difference between the chamber and the top of the piston which causes an upward movement of the piston of about ½ inch and increases the chamber volume by ½%.

The expansion that occurs in about $^{15}/_{1000}$ of a second results in a 50-psi drop in chamber pressure, which makes the liquid track-sensitive. At this time, charged particles are sent into the chamber through a thin-metal beam window in its side, and the resultant bubble tracks are photographed. The bubbles are then quenched by the recompression stroke of the piston, which is also controlled by fast-acting valves. The whole cycle is completed in less than $^{30}/_{1000}$ of a second and can be repeated once a second. To keep the chamber cycling at this high frequency requires faultless functioning of the expansion system. Expansion and recompression valves must be accurately cycled to provide sufficiently fast expansions reliably and to avoid overtravel of the piston in either direction. A continuous supply of pure gaseous hydrogen, needed to drive the expansion system, is provided by a 3-stage hydrogen compressor supplying 250-psi hydrogen gas and driven by a 150-horsepower motor.

and average density along the tracks must be uniform; this requires great accuracy in timing the photographic process and controlling the temperature. Precise and uniform temperature control throughout the chamber is also required to prevent distortion of the tracks by turbulence. Furthermore, since the tracks must not be distorted by optical effects, the optics of the chamber camera and illumination system must be nearly perfect. Maintenance of picture quality without variation from one photograph to the next requires accurately reproducible operation of the whole chamber complex from cycle to cycle. Since the magnetic field must be very well determined over the entire chamber for later correct calculation of track curvatures, it must remain very constant and must be measured precisely. A further important consideration is safety of operation, since all liquids so far used in bubble chambers are flammable or toxic or require high pressure for satisfactory operation.

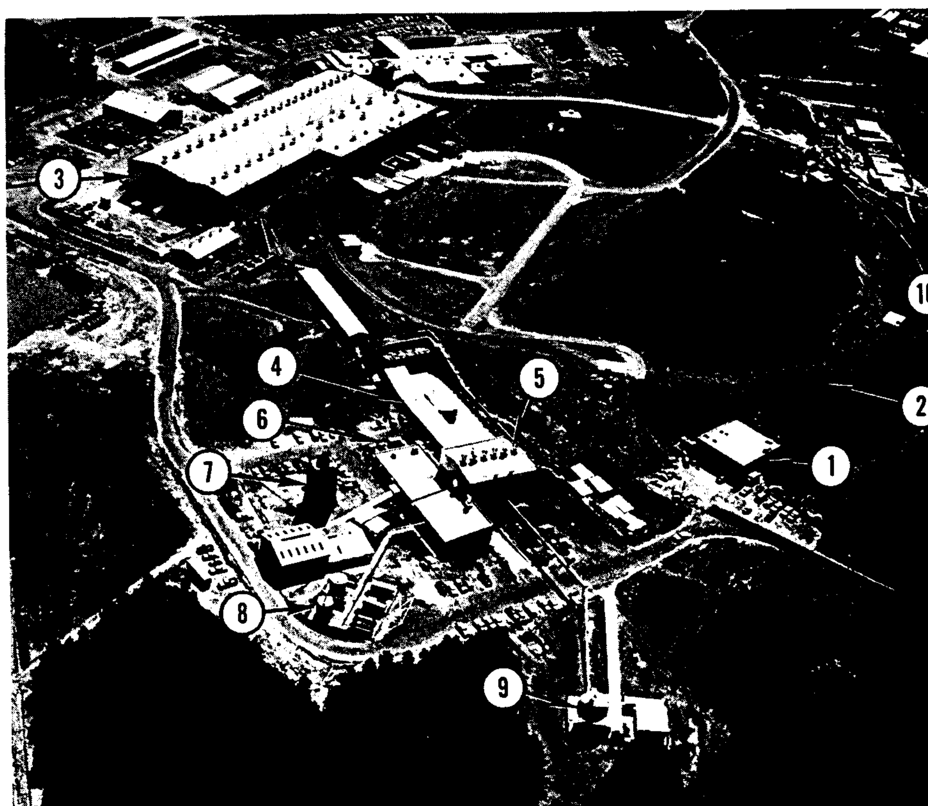


Schematic cross section of the 80-inch liquid hydrogen bubble chamber showing major components.

The 80-Inch Liquid Hydrogen Bubble Chamber

Design work for the 80-inch bubble chamber was started at Brookhaven in 1959. The entire project, including engineering design, purchasing, manufacturing, assembly, building and facilities, required a total of 250 man-years and cost almost $6 million. Four years later, on June 2, 1963, the first tracks were photographed in the chamber on the first trial run. After a number of improvements and modifications, the chamber was put into operation for physics experiments in October 1963. To date 3.3 million pictures have been taken for 29 experiments scheduled for groups of physicists from 17 universities and laboratories, including Brookhaven. Fifty people including technicians, engineers and physicists are required to operate and maintain the chamber 24 hours a day, 7 days a week.

The 80-inch bubble chamber is located in a high-bay area in a 62 by 74-foot building 41 feet high, equipped with a 40-ton overhead crane and provided with adequate ventilation for a fast air change in case of undesired hydrogen release into the room. One-foot-thick concrete walls separate the high-bay area from the compressor and control rooms. Located outside, in addition to the gas storage area and the safety sphere, is a redwood cooling tower 47 feet high which cools the recirculated water carrying off the heat dissipated by the bubble chamber magnet and the beam magnets, a total of 12 megawatts.



Aerial view of the Brookhaven Alternating Gradient Synchrotron (AGS) and 80-inch bubble chamber complex. (1) AGS injector building housing the Cockcroft-Walton machine and section of linear accelerator; (2) circular tunnel containing the 843-foot diameter AGS magnet ring; (3) main experimental area; (4) particle beam array for 80-inch bubble chamber; (5) 80-inch chamber building; (6) transformers for electric power for the 80-inch chamber magnet and other major components; (7) water cooling tower; (8) gas storage area; (9) safety sphere; (10) beam direction in AGS.

This process occurs in a bubble chamber by the following mechanism: When an electrically charged particle travels through any material, its moving electric field causes motion of some of the charged particles (electrons and nuclei) in the material. Sometimes these particles are bounced fairly far from their original positions, but most frequently the collisions are less energetic, and only a few hundred electron volts of energy are transferred from the incident particles to the particles in the material. When this material is the liquid in a bubble chamber, the resultant agitation is quickly shared among the local molecules and forms the heat spike necessary for bubble formation. If the container volume is expanded, and the charged particle passes through the liquid at the correct instant during this expansion, then the string of heat spikes left along the particle's path produces a track of very fast-growing bubbles. A light flashed shortly after the passage of the particle allows a photograph of the track to be taken. If an incident particle hits one of the nuclei in the liquid, then its own track may stop abruptly at the point of collision, and other tracks caused by the fragments may start there. This nuclear interaction may turn out to be one of the events to be studied in detail. For practical reasons and to allow frequent repetition of the process, the liquid is rapidly returned to its compressed condition so that the bubbles are forced to collapse and return to the liquid state.

As described below in more detail, most bubble chambers are mounted in magnets. A magnetic field deflects moving charged particles. The resultant curvatures in the tracks are used to determine the momenta of the particles. The momentum depends on a particle's mass and velocity and is needed for calculations to be performed on events.

After a series of photographs has been taken, the photographs are scanned on projectors for events of interest, and then the tracks of the events are measured very accurately – to an accuracy of a few ten-thousandths (10^{-4}) of an inch. Because of the very high precision required, bubble chambers themselves must be precision instruments. The photographed bubbles must be small, and their size

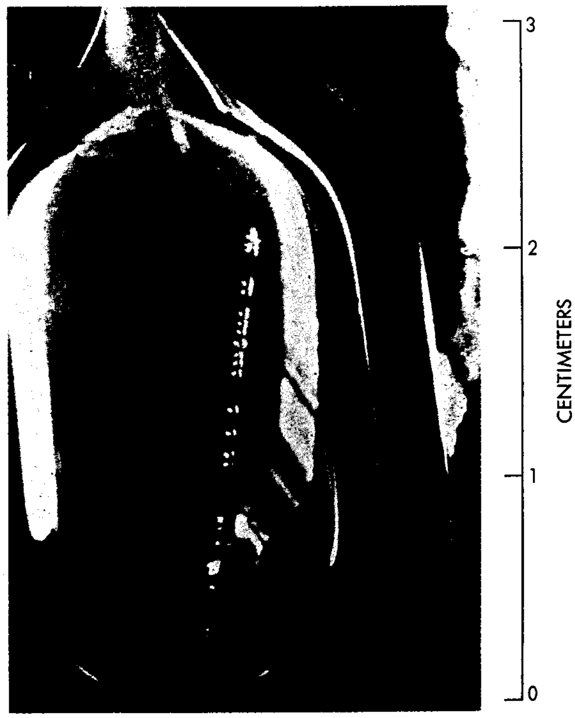
Design and construction of the Brookhaven AGS, a proton accelerator employing a strong-focusing principle and designed to accelerate protons up to energies of about 33 BeV, was begun in 1952. Satisfactory operation started in 1960. This machine is described in another booklet called *The Brookhaven Alternating Gradient Synchrotron*. In order to exploit the opportunities offered by the AGS, design was begun in 1959 on a liquid hydrogen bubble chamber 80 inches in length.

How a Bubble Chamber Works

The mechanism by which a bubble chamber operates may be explained as follows. Every liquid gives off a vapor. If the liquid is enclosed in an insulated, sealed container, it exerts a vapor pressure, which depends on the temperature of the liquid. If the volume of the container is subsequently increased, liquid evaporates to fill the additional space with vapor. This occurs almost instantaneously: the liquid boils briefly with bubbles forming at the container walls. Inside the liquid there is much less boiling because its molecules cling together very tenaciously (if they didn't, only gases would exist, not liquids or solids) and because heat must be transferred to the bulk of the liquid. For a bubble to form, some special condition is needed to start an extremely small "break" in the liquid. For instance, a dust particle or some other mechanical irregularity can break the coherence of the liquid; this is one reason why boiling occurs easily along container walls that are not perfectly smooth. Or a tiny amount of extra energy in the form of heat might be localized in a minute space in the liquid, only a few billionths of an inch in size. Heat means motion of molecules, and extra heat means extra agitation counteracting the coherence of the molecules. Thus a local hot spot can cause a "break" resulting in bubble formation. If a microscopic heat spike is produced somewhere in the liquid simultaneously with an increase in the container volume, then a bubble will form at that point and continue to grow until equilibrium is restored.

motron) and received the Nobel Prize for this achievement in 1960. Glaser's first chamber consisted of a very well-cleaned small glass bulb, but he and other experimenters soon found that for practical purposes the chamber walls need not be extremely clean. Thus it was possible to construct chambers with metal walls, glass plates, gaskets, pipe lines, and other standard engineering materials, and the way was open for construction of chambers of almost unlimited size.

Many different liquids can be and have been used in bubble chambers. Hydrogen is perhaps the most universal one, but propane, Freon, liquid xenon, and more recently neon-hydrogen mixtures, all have properties that may be desirable in some experiments. Specifically, the heavier liquids produce more events because their nuclei, being larger, are more easily struck by an incident particle. Events in heavier liquids usually are difficult to analyze, but neutral particles from an event are fairly easily detected because secondary reactions in these liquids yield charged particles.



The 3-cm × 1-cm-diameter glass bulb in which bubble tracks of charged particles were first observed by Donald A. Glaser.

No two bubble chambers are constructed exactly alike, but all operate on the same basic principle. The first large liquid hydrogen chamber, 72 inches in length, was designed and built at the University of California in Berkeley, where the Bevatron, a 6-BeV accelerator, had come into operation. As will be shown later, the higher the energies to be investigated, the larger the desirable chamber size. Many special low-temperature (cryogenic) techniques had to be developed, since liquid hydrogen (also deuterium or neon) must be kept at temperatures below $-400°$F. At Brookhaven two chambers, one 14 inches in diameter and the other 20 inches long, were completed in 1959 for use at the Cosmotron.

plus the vapor of a liquid and equipped with glass windows. By cooling the gas the vapor is supercooled so that it forms droplets where an electrically charged particle has passed. The resulting tracks are quickly illuminated and photographed.

Until 1952 the only source of particles with energies high enough to cause interactions of special interest was cosmic radiation. Particles, often from outer space, entering the atmosphere from all directions, made many interesting studies possible. But it was not easy to separate any special kind of particle for study, and there were not very many to select from. Then the advent of large particle accelerators such as the Brookhaven Cosmotron enabled experimenters to select particles by their masses, velocities, or momenta and to collimate or focus them to obtain precisely the right conditions for an experiment. The Cosmotron could produce particles with energies up to 3 billion electron volts (BeV), much higher than the *average* energy of cosmic radiation. (A particle with one electron charge acquires one electron volt of energy when it passes through a potential difference of one volt.) The particles from the Cosmotron were sent through cloud chambers, and many interesting events were observed due to collisions between an incident particle and a nucleus of an atom contained in the chamber gas. Hydrogen was an especially interesting gas for use as a target because, since the hydrogen nucleus is simply a proton, the collisions were not obscured by secondary effects due to the other particles present in heavier nuclei. Deuterium gas was also useful, since its nucleus contains only one neutron bound to the proton. To produce more collisions, cloud chambers could be made to contain more target nuclei by increasing the gas pressure. But for reasonably good operation the pressure could not be very high, and the number of events of special interest remained too low.

Since liquids are much denser than gases and gas bubbles are certainly visible in liquids, a number of researchers considered the possibility of using liquid targets in which bubbles would form along the paths of electrically charged particles. Donald A. Glaser at the University of Michigan invented the bubble chamber in 1952 (just when the first experimental results were being obtained at the Cos-

If two billiard balls were to collide at high enough velocities, they would either crack and shatter immediately or oscillate violently for a brief period and then fall apart (decay) into several fragments; this would be an example of an inelastic collision. By studying the numbers, sizes, velocities, rotations, and directions of flight of the fragments it should be possible to draw conclusions about the forces that held each ball together before the collision and made them shatter afterwards. Similarly, the short-range nuclear forces can be studied by analyzing the products of inelastic collisions occurring at high velocities, near the velocity of light. According to the theory of quantum mechanics, forces between particles are due to the exchange of quanta (discrete packets of energy). For instance, the electric force between the proton and the electron is due to the exchange of light quanta called photons. Under proper experimental conditions the photons themselves behave as particles although they propagate as electromagnetic waves. The stronger and shorter-range the forces, the heavier the quanta, and the more clearly can the quanta be identified as particles. These quantum-particles themselves, if they live long enough, can collide with nuclei and produce still other new particles. So far almost 100 different such subatomic particles have been identified. Thus the field of high energy physics is also called particle physics – and it has become one of the most vexing, exciting, and scientifically rewarding areas of research.

Particle Detectors and Accelerators

When few particles of interest are involved in an interaction, their paths and flight times can be recorded by letting them pass through recording devices such as electronic counters, and this is still an important technique. However, as more particles become involved, if details on every observed interaction are needed, the paths of the particles must be made visible to make detailed measurements possible. Until 1952 this was done with cloud chambers or with special photographic emulsions. In the latter the particles interact directly with the nuclei of the atoms contained in the emulsion. A cloud chamber consists of a box filled with a gas the masses, electric charges, mean lives, and other more subtle properties of the particles can be determined. Insight into the nature of the forces that act between nuclear particles can then be gained from the types and numbers of particles observed and from the details of many events studied. An understanding, including a correct mathematical description, of these forces, and the formulation of laws explaining their properties are central goals of high energy physics. Experimental investigations now being done are leading the way to new theoretical concepts which in turn are used to predict further experimental results. Through this interplay between theory and experiment, the field of physics has come a long way; it probably has a long way to go before all the observed phenomena can be explained and understood.

Nuclear Forces and Interactions

When two billiard balls collide, their surfaces are slightly compressed at first and then spring back, and the balls are propelled in certain new directions; the balls are elastically scattered by the compression forces acting between them. Since the balls must touch each other before these forces can act, this might be called an interaction at *short* range. An elastic interaction at *long* range occurs when the path of a comet passing near the sun is altered by the gravitational force of the sun acting on the comet. A similar but very much stronger force, due to the electric charges, acts between atomic particles. An example of the action of this electric force is the elastic scattering of an electron by a proton. (The proton is the simplest existing nucleus, that of hydrogen. At low relative energies an electron and a proton can be bound together by the electric force to form a hydrogen atom.) Other kinds of forces include the magnetic force, which acts similarly to the electric force; the weak interaction force, which, among other things, plays an important role in radioactive decays; and the strong short-range nuclear interaction force, which, for example, binds protons and neutrons together to make heavier nuclei. The latter two forces are at present under intensive investigation.

Introduction

The physics of elementary particles, often called high energy physics, is concerned with the properties and interactions of nuclear particles. Experimental work in this field has two basic aspects, the production and the detection of the particles whose characteristics are being studied. High energy physics is one of the important branches of science today, and one of its basic research tools is the bubble chamber. Many kinds of apparatus and machines have been devised to extend man's knowledge of the universe. Enormous telescopes are used to observe phenomena in the sky too remote for direct observation, and microscopes enable the human eye to see minute objects and organisms. But the atom is far too small to be seen even with the most highly magnifying microscope. Various types of detectors have therefore been devised to study the atom and subatomic particles; among these, the bubble chamber is one of the most useful. The 80-inch liquid hydrogen bubble chamber at Brookhaven is the largest now in existence; it is used in conjunction with Brookhaven's Alternating Gradient Synchrotron (AGS), at present the world's most powerful accelerator.

In a bubble chamber, collisions and interactions between nuclear particles take place. If the particles come sufficiently close to each other, the collisions can cause them to generate new particles or to break up into other elementary particles, which, if electrically charged, produce tracks of bubbles along their trajectories through the liquid contained in the bubble chamber. Thus, although the particles cannot be seen directly, their tracks give evidence of their existence and provide information concerning their properties. From measurements and computations on observed events and the application of basic physical laws, a great deal of knowledge about nuclear particles can be gained from bubble chamber tracks. The geometry of the tracks and the curvatures produced by magnetic fields and also the observed number of bubbles along a track provide data from which

The selection process starts at a wall of heavy metal with a small slit in it, mounted near the target struck by the protons. A number of particles pass forward through the slit, toward the chamber. Next, particles with the desired momenta and sign of electric charge are selected by a magnet which deflects them further toward the chamber. At this point the beam of particles, as defined by the target and the slit, has diverged to such an extent that not enough particles may be left to enter the chamber. Therefore, a focusing magnet, which may be compared to a lens focusing light, is used to gather together (or focus) the particles to prevent further divergence. These various magnets have the same effect as the large 80-inch chamber magnet: they curve the trajectories of the particles and thus alter their directions of flight in a precisely determined manner.

At this point particles of selected momenta are traveling at high speeds toward the chamber, but the selection process is not yet complete because particles of different masses can have identical momenta since momentum depends on both velocity and mass. To select the desired masses the particles are passed through a beam separator, where a strong electric field is applied in a direction perpendicular to the flight path of the particles. The electric field is produced between two metal plates, which may be 4 inches apart and 15 feet long, and may amount to a gradient of 100,000 volts per inch between the plates. Since an electric field deflects the particles according to the product of their velocities and momenta, for selected momenta the heavier particles are deflected more than the lighter ones, and the trajectories are again altered so that the particles emerge from the beam separators in slightly different directions corresponding to their masses. All that remains is to focus the particles on another heavy metal wall where a slit is located in the correct position for passage of the desired particles, and a separated beam of particles of the desired mass, electric charge, and momentum emerges. Sometimes only a few such particles are left when those of interest for an experiment are separated from the many more common ones. Also, the array of magnets and separators can become so long that many of the desired particles decay long before they reach the chamber. Nevertheless, beams of pro-