A high-pressure diffusion cloud chamber in a pulsed magnetic fiel

By A. P. Batson, B.Sc., P. N. Cooper, B.Sc., Ph.D.,* and L. Riddiford, M.Sc., Ph.D., A.Inst.P.,
Department of Physics, University of Birmingham

[*Paper received* 26 *March*, 1956]

A description is given of an 18 in. diameter high-pressure diffusion cloud chamber constructed for use with the Birmingham proton synchrotron. The associated equipment to provide a pulsed magnetic field of 13 kG at each synchrotron pulse is discussed and an account of the operation of the apparatus is given.

A conventional cloud chamber is sensitive to ionizing radiation for only a short time, of the order of one-tenth of a second, after the adiabatic expansion. Further, especially for high-pressure chambers, the time interval between successive expansions is long. This makes such an apparatus uneconomic for a study of interactions with the gas in the chamber, when it is used with a high energy particle accelerator such as the Birmingham proton synchrotron, which produces a pulse of particles every few seconds. The diffusion cloud chamber is continuously sensitive to low levels of ionizing radiation, and so does not suffer from these limitations. Such a chamber was first operated in 1936 by Langsdorf,(1) and in 1950 accounts of chambers of simpler design were published.(2,3) The principle is as follows. The top of the chamber is maintained at room temperature, whilst the base is cooled to a very low temperature. Close to the top is a reservoir of a suitable liquid (usually methyl alcohol), which saturates the surrounding gas with vapour, and at some level in the chamber the temperature will be low enough for there to exist a sufficient degree of supersaturation to cause condensation on ions.

The possibility of using a diffusion cloud chamber for experiments with particle accelerators led to the development of the theory in some detail by Shutt.(4) Bevan(5) has shown that the theory is in accord with experiment. In 1951 Shutt and his collaborators succeeded in operating such a chamber at high gas pressures and with high repetition rates using a pulsed source of radiation.(6,7) Subsequently the same experimental group(8) described two chambers for experiments with the Brookhaven cosmotron, both operating at a hydrogen pressure of twenty atmospheres. One is a circular chamber for use in a magnetic field, the other a very large one which permits considerably more gas to be exposed to the beam of particles in use. The decision to construct a diffusion cloud chamber and magnet for use with the Birmingham synchrotron was taken early in 1953, and it was completed in the latter half of 1954. Equipment of a similar nature has been built at Chicago,(9) Harwell(10) and Liverpool.(11) A complete account of an installation of this kind has not been given. This paper describes the equipment constructed at Birmingham, which has been used to study proton–proton interactions at 650 MeV, as reported in a separate paper by two of the authors.(12)

THE CLOUD CHAMBER

The chamber is 18 in. in diameter, and is of the downward diffusion type. Fig. 1 shows its main features. The construction is in two parts, the lower cylindrical section being the effective part of the chamber, the upper conical section completing a convenient design. The cylinder and ports for illumination are formed from $\frac{1}{4}$ in. thick stainless steel sheet, this being sufficient to withstand the test pressure of thirty-fi atmospheres. The relatively low thermal conductivity stainless steel means that less heat is required to maintain given temperature gradient in the wall. Furthermore, as th chamber operates in a pulsed magnetic field, the use of thi non-magnetic material of high resistivity minimizes distortions in the field and the effects of eddy currents. The base of the chamber is a $1\frac{1}{2}$ in. thick mild steel disk. The use of mild steel improves the magnetic circuit substantially, reducing the power required to provide a given magnetic field. A thin-walled copper pipe of $\frac{1}{2}$ in. outside diameter, in the form of a spiral, is soft-soldered to the base. Commercial methyl alcohol at a temperature of about −70° C is pumped through this coil and maintains the temperature of the baseplate at about −60° C. The methyl alcohol is cooled by

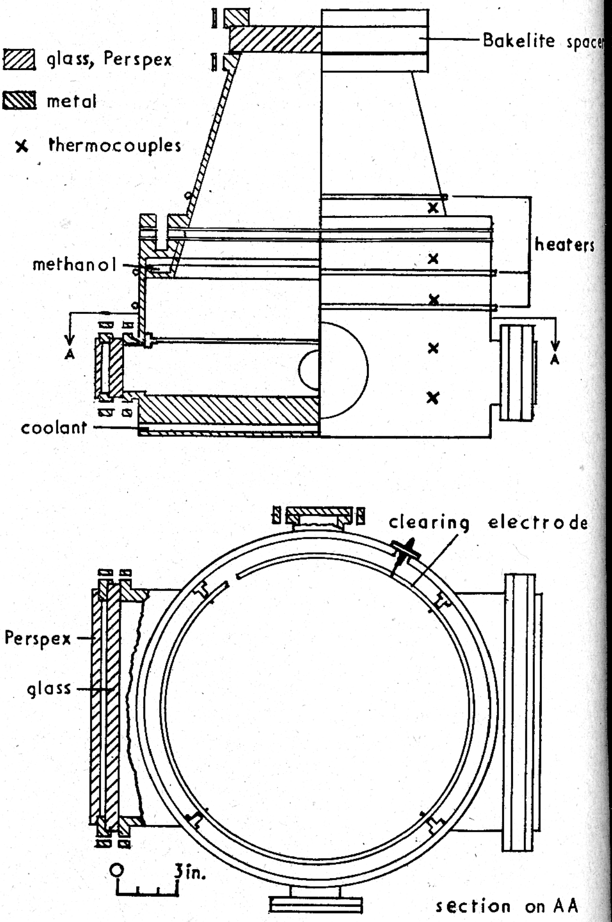

Fig. 1. The diffusion cloud chamber

---

* Now at Associated Electrical Industries, Aldermaston, Berks.

passing it through a heat exchanger consisting of a 21 ft length of $\frac{1}{2}$ in. copper tubing, in the form of a spiral, placed in an equilibrium mixture of commercial methyl alcohol and solid carbon dioxide contained in a large drum. The coolant is circulated by a 200 W Stuart-Turner centrifugal water pump, modified for low temperature work by thermally insulating the pumping chamber from the pump motor. This has a capacity of several gallons per minute at the pressure in question.

The tray from which the methanol vapour is supplied is an annular brass trough, 1 in. deep and about $\frac{3}{4}$ in. wide, slit at one point to minimize eddy currents. It has a capacity of about one litre, and so supplies sufficient vapour for several days continuous operation without refilling. It may be refilled, without releasing the high-pressure gas in the chamber, from a reservoir of capacity about one litre which is connected to a drain in the chamber base. The tray is solidly thermally connected to the top of the lower part of the chamber, and is located so as not to obstruct the camera's view of the sensitive region. A clearing field removes ions which would otherwise diffuse into the sensitive layer and deplete the supply of vapour, and facilitates the removal of old tracks between pulses of radiation. The electrode is in the form of a (slit) ring of thick copper wire supported at four points by ceramic insulators fixed to the wall of the chamber. It is normally maintained at a negative potential of 1000 V, the high voltage being brought through the wall of the chamber on a K.L.G. metal-ceramic seal, soft-soldered to a small brass flange. The clearing field is removed about four seconds before each pulse of particles enters the chamber, to prevent old cosmic ray tracks, made extremely diffuse by the action of the field, from forming an unpleasant background. Four seconds is sufficient time for these tracks to fall through the sensitive layer. The sides and base of the lower section of the chamber are lined with black velveteen to minimize the amount of scattered light. The velvet on the base must be covered with a pool of methanol to prevent the pile from scattering obliquely incident light from the flash tubes into the camera. Recently the base velvet has been removed and a small quantity of the black dye Nigrosine (by I.C.I. Ltd.) dissolved in the methanol to provide a satisfactory photographic background. The upper part of the chamber is constructed from $\frac{1}{4}$ in. mild steel sheet, and is thermally insulated from the bottom part by a Bakelite spacer. This insulation makes the performance essentially independent of the temperature of the top, which may be kept quite warm to prevent a mist of methanol forming on the viewing window. The large volume of the top part of the chamber should ensure a good flow of vapour to the centre of the sensitive region. Photographs are taken through the $1\frac{1}{4}$ in. "armourplate" viewing window* at the top of the cone. The two side windows are of $\frac{7}{8}$ in. thick "armourplate." Since these windows are close to the cold base, to minimize frosting a $\frac{1}{4}$ in. thick sheet of Perspex is fitted in front of each, forming a double window. The pressure seals are made by $\frac{3}{16}$ in. square soft rubber gaskets located in rectangular grooves, and compressed by bolts sufficiently large to withstand the pressure on the area concerned. Bakelite spacers between flanges ensure a uniform distribution of stress on the glass whilst allowing adequate compression of the rubber. Fibre washers are used as cushions between metal and glass surfaces.

The temperature gradient in the wall of the chamber is controlled by means of three electrical heaters encircling it in the positions shown in Fig. 1. Each heater consists of a 22 gauge Brightray wire (by Henry Wiggin and Co. Ltd.) on to which are threaded overlapping ceramic beads, the whole being enclosed in a $\frac{5}{16}$ in. outside diameter copper tube soft-soldered to the chamber wall. Five identical copper-constantan thermocouples, located as in Fig. 1, are used to measure the temperature distribution. The whole of the chamber, except for the windows, is lagged with a 1 in. thick layer of felt which assists in thermally insulating it from the magnet in which it is enclosed. Before filling with hydrogen, the chamber and reservoir are evacuated to an air pressure of less than 1 cm of mercury with a mechanical vacuum pump. This ensures that not more than 1% of the interactions observed at a pressure of 25 atm are with nucleons other than free protons.

Shutt(4) predicts a minimum temperature gradient in the sensitive volume of about 6·3° C/cm for satisfactory operation at this pressure. The best operating conditions with the present chamber are achieved with a temperature gradient of 6·8° C/cm in the sensitive depth and a much lower gradient between this and the vapour source, which is normally at about 23° C. If the vapour source temperature is increased above this value the sensitive depth increases a little, but there is a danger of general instability of the gas-vapour mixture. Gaps appear in the tracks which form mainly in regions of rather dense "rain." Satisfactory operation at a lower tray temperature of 10–15° C is possible if a velveteen

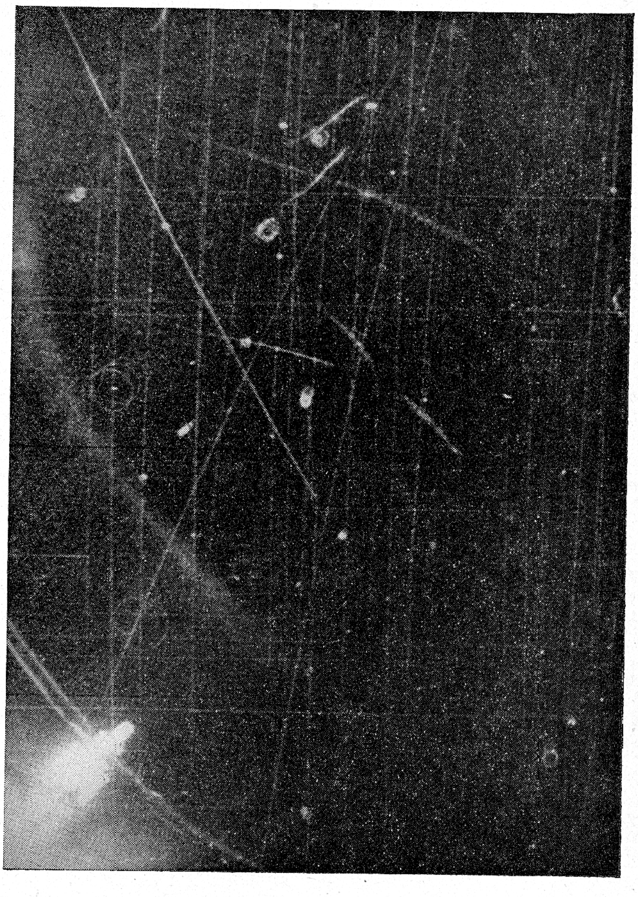

Fig. 2. Typical 650 MeV proton tracks. The reaction is of type $p + p \rightarrow n + p + \pi^+$

---

* Because of the optical distortions resulting from this window, it has now been replaced by a stainless steel plate on to which are fitted small windows of optically flat plate glass.

wick, dipping into the methanol tray and covering the entire surface of the conical section of the chamber, is added. However, the maximum safe operating temperature is correspondingly lower, and it is often not possible to maintain the tray temperature below 15° C under operating conditions because of the flow of heat into the chamber from the magnet coils and the eddy current heating in the chamber walls.

A sensitive depth of $2\frac{1}{2}$ in. is normally obtainable under ideal conditions, but the average sensitive depth throughout a full day's operation in conjunction with the synchrotron is usually only about 2 in. For an air filling at a pressure of three atmospheres a sensitive depth of $3\frac{1}{2}$ in. is readily obtainable. Normally the temperatures can be maintained close to the ideal ones throughout a long run by occasional adjustment of the heater settings. Considerable difficulty has been experienced at times due to quite large insensitive or less sensitive regions in which tracks do not form. Presumably these arose from the azimuthal asymmetry in the temperature gradient which must exist on account of the presence of the illumination windows. They have not been observed since thin sheets of Perspex were placed in the chamber in front of the windows to isolate the gas within the windows from that in the main part of the chamber. Tracks form within about 1 cm of the Perspex sheets. Normally excellent tracks are obtainable throughout the entire chamber. An example of such tracks is given in Fig. 2, which also shows a reaction of the type $p + p \rightarrow n + p + \pi^{+}$. The 650 MeV proton tracks are curved in the field of 13 000 G. Up to thirty high-energy tracks of minimum ionization density, plus the associated background, may be passed through the chamber at each synchrotron pulse without any apparent deterioration in performance. If the ionization level exceeds this, however, the appearance of the sensitive volume deteriorates because of the resultant depletion of the flux of vapour.

THE PHOTOGRAPHIC SYSTEM

The light source consists of two 400 J xenon-filled flash tubes (type LSD16 by Mullard Ltd.), one on each side of the chamber. Each tube is situated at the focus of a cylindrical lens $2\frac{1}{4}$ in. high, and connected to a condenser bank of capacity 132 μF at a potential of 2500 V. Since the tubes are in a quite strong pulsed magnetic field, to prevent breakages they are held in clamps of copper strip which grip them firmly but are themselves not quite rigid. The camera takes stereoscopic pairs of photographs through two Dalmac $f/3\cdot5$ lenses of focal length 2 in. (by J. H. Dallmeyer Ltd.) placed symmetrically one on each side of the axis of the cloud chamber. The angle between lenses as seen from the sensitive layer is about 10°. The aperture should not exceed $f/8$ to maintain an adequate depth of focus. Photographs are taken on 60 mm wide type 5G91 recording film (by Ilford Ltd.) and developed in X-ray developer type D19b (by Kodak Ltd.). The film is guided through the camera by rollers, and kept flat by pressure plates to which the condenser lenses required for satisfactory reprojection are attached. It is exposed in 100 ft lengths, each of which lasts about fifty minutes when pairs of photographs are taken at ten second intervals. The de-magnification factor is ten. The film is wound on after a photograph by a 24 W motor which drives a shaft connected to the wind-on spool in the camera. The motor is switched off after the film has moved the appropriate distance, by a cam-operated microswitch, the cam being driven by two sprocket wheels which engage in the film perforations. A significant interval of time must elapse between the instant of particle entry and the instant of photography. This time is kept as short as possible to minimize possible errors in momentum measurements d to convective gas flow during the interval. For the experim described in Ref. 12 the time interval was 0·15 s, but t has now been reduced to 0·12 s as a result of improveme in the illumination system. The pulse of particles from t synchrotron has a duration of several milliseconds only.

For analysis of the photographs, the film is replaced in t camera, and illuminated from a 250 W pre-set focus pr jection lamp mounted at the top of a reprojection table. T film may be accurately re-located in the camera if the di phragm in front of the film is also the limiting stop in t reprojection system. The reprojection table is free to mo a distance of $3\frac{1}{2}$ in. in the vertical direction and 15 in. in t direction of the horizontal line joining the axes of the tw camera lenses. It may be rotated freely about the vertic axis, and also to angles of ±75° about a horizontal axi Once the stereoscopic images have been made to coalesc small electromagnets make it possible to lock the table i any position, whence angles may be read on protracto attached to it. Since all primary tracks move approximate in the horizontal direction, the degrees of freedom a adequate for the investigation of almost any interaction i any part of the chamber. Curvatures are measured by com parison with arcs very carefully drawn on stiff board. Th track in question is alined at right angles to the horizonta axis of rotation of the table, and the apparent curvature i space measured after the two images have been broug together. Only a dip angle correction is then necessary t obtain the true momentum in space.

THE MAGNET

The cloud chamber is placed in a strong magnetic fiel which makes possible measurements of the momenta o particles whose tracks are photographed within it. Th general features of the seven ton magnet with the chambe installed are shown in Fig. 3. The assembly is mounted o a stout trolley and Fig. 4 shows a photograph of the complet equipment. The base of the chamber rests on a 20 i diameter pole, and is thermally insulated from it by a $\frac{1}{2}$ i thick ring of Bakelite and a packing of glass wool. The to of the chamber fits into a conical hole machined in the uppe member of the yoke, which may be removed to allow acces to the chamber should this be necessary. To minimize powe consumption and avoid overheating of the windings, th magnet is designed for pulsed operation, yoke and pol being constructed from $\frac{1}{2}$ in. thick steel plates. Care is take in the construction to avoid loops in which eddy current would circulate.

The coil boxes shown in Fig. 3 each contain six coils Individual coils consist of 108 turns of $\frac{3}{4} \times 0\cdot070$ in. coppe strip wound into a tight spiral, the insulation between turns being presspahn paper 0·010 in. thick. Insulation betwee coils is provided by $\frac{1}{2} \times \frac{5}{32}$ in. strips of Bakelite, twelve pe interlayer. The top and bottom of each coil box is a $\frac{3}{8}$ in. thick sheet of stainless steel, and the inner and outer walls are cut from sheet Bakelite. The greatest electrical stresses exist between the coils adjacent to the stainless steel plates and the earthed plates themselves. To avoid the possibility of "tracking" following the accumulation of dirt and moisture in an air-cooled system, the insulation in these areas i supplemented by the addition of $\frac{1}{16}$ in. thick Bakelite shee liners covering the stainless steel plates. The coil assemblies are made mechanically strong by pulling the plates togethe with stainless steel bolts, insulated with Bakelite sleeves Forced air cooling is supplied to each box from a fan mounte

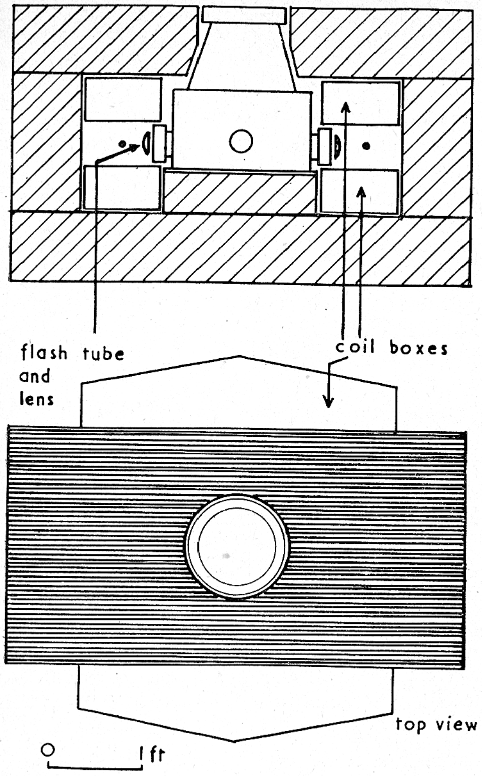

Fig. 3. Cloud chamber and magnet assembly

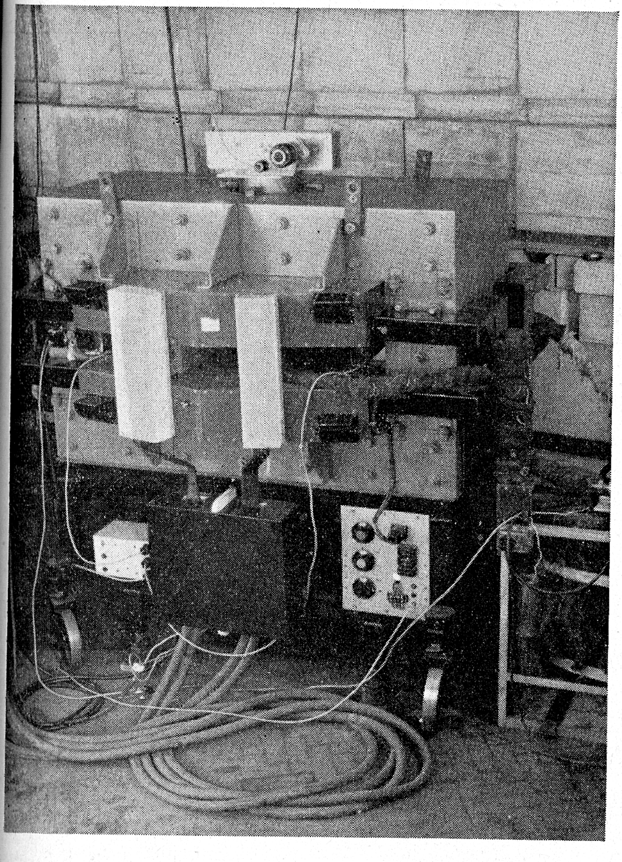

Fig. 4. General view of the equipment

on the magnet trolley. The fan is of the high speed axia flow type with a speed of 2900 rev/min, capable of deliverin 1700 ft^3/min into a pressure head of $1\frac{1}{2}$ in. of water. Ai circulates between the Bakelite spacers and is guided throug the box by Bakelite baffles in such a way as to provid uniform cooling and a minimum resistance to the flow.

Each pair of coils is connected in series and the six pair are excited in a series—parallel arrangement from a 500 kW d.c. generator, normally used to supply the magnet of the Nuffield Laboratory 60 in. cyclotron. The effective number of turns is 648, and in the present case the generator provides 400 V and 500 A peak to the cloud chamber magnet. The power circuit is drawn schematically in Fig. 5(a). To achieve a rapid build-up and shut-down time of the generator voltage, its field windings are excited from a 20 kW pilot exciter supplying about 515 V. A potential of about 65 V across the field windings is required to obtain an output of 450 V from the generator. The field windings and exciter are connected in series across the armature of the main generator. When the

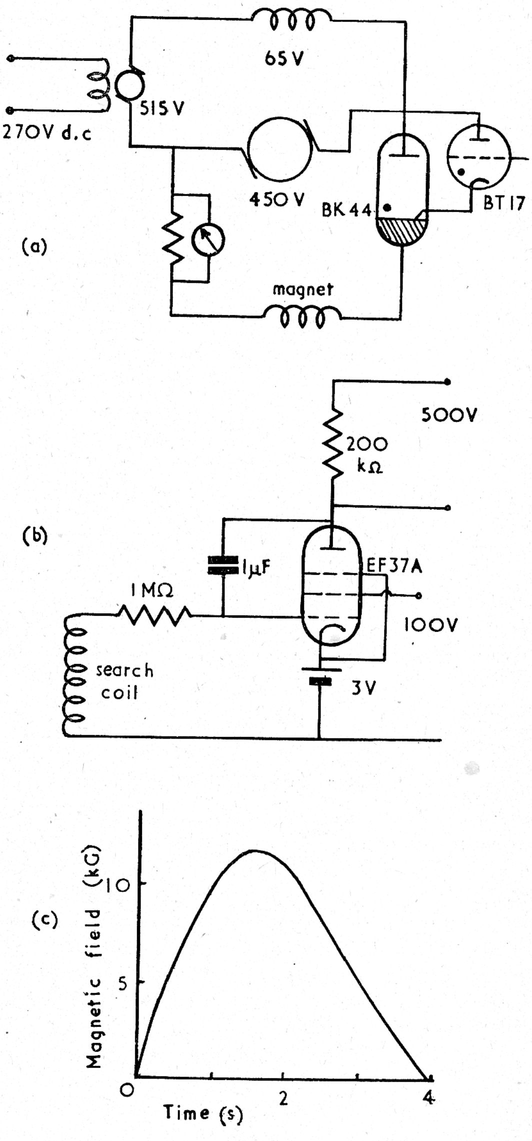

Fig. 5. (a) Magnet excitation system. (b) Miller integrator circuit. (c) Typical magnetic field pulse

pilot exciter is switched on a potential of 515 V is applied to the field windings, resulting in a rapid rise in the armature potential to 450 V, when the potential across the field windings has decreased to the equilibrium value of 65 V. At this stage the current to the magnet is switched on by means of a water-cooled metal ignitron (type BK44 by British Thomson-Houston Co. Ltd.). This is done by what manufacturers call an "anode firing" circuit. A type BT17 mercury vapour thyratron (by British Thomson-Houston Co. Ltd.) is connected across the anode and the igniter of the ignitron so that its anode potential is supplied from the generator. When a positive potential is applied to the grid of the thyratron, the anode current of the thyratron triggers the ignitron, to which the current is transferred, the potential across it falling to such a value that the thyratron goes out. The current to the field windings of the exciter is reversed about one second after the main current has started. This causes a potential of −965 V to appear across the main field windings, forcing the output potential of the main generator to a negative value. The ignitron current reaches its maximum value of about 500 A in 1·3 seconds, and thereafter decreases, becoming zero after 4 seconds when the ignitron goes out, the excitation of the pilot exciter being removed some time before this. For the best accuracy in timing, this excitation is applied, reversed and broken by spring-loaded high-speed relays placed in the 270 V, 0·6 A d.c. side of the power supply.

For one pulse every ten seconds, the mean power dissipation in the coil is about 15 kW and the air emerging from the coil boxes has an equilibrium temperature of 60–65° C. Various safety devices are incorporated to disconnect the field supply to the exciter in the event of trouble. These comprise an overload relay operated from the shunt to the main current ammeter, a water switch in the ignitron cooling system, a thermostat attached to what should be the hottest place in the coil box, and a centrifugal switch on the fan.

The magnitude of the magnetic field has been measured under both steady and pulsed conditions. The steady-state measurements were made with search coils and a Grassot fluxmeter, and also by Mr. H. R. Shaylor using the proton resonance apparatus designed by him for use in the magnet of the 60 in. cyclotron. The two methods gave results which agree to within 1%. The pulsed field was observed by integrating the signal from a large search coil of area—turns $8 \cdot 31 \times 10^5$ turns. cm^2. The output potential from this coil is sufficiently large without amplification to make accurate measurements on an oscilloscope trace possible. Consequently a simple Miller integrator circuit as drawn in Fig. 5(*b*) was constructed, and traces showing magnetic field as a function of time recorded [Fig. 5(*c*)]. The linearity of the integrator and the sensitivity of the oscilloscope in both potential and time were carefully checked. The peak magnetic field measured by this means agreed to within 2% with that recorded for steady-state operation at the same current as the peak value recorded by the ammeter under pulsed conditions. Further, it was shown that the peak ammeter reading was equal to the peak current to within 1%. Thus the magnetic field measurements were consistent within themselves, and it is possible to use the peak ammeter reading as a measure of the magnetic field. The spatial variation of the field was measured under steady-state conditions by a difference coil method using a fluxmeter. The distribution depends quite strongly on the degree of excitation. At the current normally used (500 A) the extreme variation within the sensitive volume is ±6%, which is of the same order as that usually found for cloud chamber magnets of this type. The worst variations occur near the outer edge of the chamber. The mean field for 500 A is taken to be 13 000 G, and repeats from pulse to pulse to within ±1%.

The timing sequence for cloud chamber operation must be related to the synchrotron cycle. Synchrotron timing is derived from a precision rotating condenser which controls the frequency of the accelerating potential in this machine.(13) Light flashes from mirrors attached to this condenser are used to regulate the speed of a synchronous motor, which drives a cam used to tune the radio-frequency power amplifier. The cloud chamber timing is derived mainly from a series of microswitches operated by cams attached to a shaft which is suitably geared to the shaft of the synchronous motor. The magnet timing is adjusted so that the field has its maximum value when the pulse of high energy particles appears. This may be simply done by observing the output from the integrator and the pulse of particles recorded by a scintillation counter on a cathode-ray tube. The adjustment is not critical since the top of the magnetic field pulse is quite rounded. The cam-switches are also used to wind on the film in the camera between photographs, and to remove the clearing field at the appropriate time, as described previously. The flash tubes are triggered by a pulse from one of the mirrors attached to the precision condenser. One of the cam switches operates a selector switch and relays so that, if required, the cloud chamber sequence and acceleration of the synchrotron beam occur only at each second, third or fourth synchrotron cycle. This makes satisfactory operation possible should the level of background ionization associated with any beam be too high to permit the use of the diffusion chamber each synchrotron pulse.

ACKNOWLEDGEMENTS

We are grateful to Prof. P. B. Moon for his interest in this work. The apparatus could not have been constructed without the skilful technical assistance of Mr. C. C. Barrow and Mr. R. H. Joines. During the past year Mr. B. Culwick has made substantial contributions to its improvement. The guidance of Dr. F. Aughtie in the design of the excitation system was invaluable. The cost of the equipment was borne by the Department of Scientific and Industrial Research, to whom two of us (A. P. B. and P. N. C.) are grateful for maintenance grants.

REFERENCES

(1) LANGSDORF, A. *Rev. Sci. Instrum.*, **10**, p. 91 (1939).
(2) COWAN, E. W. *Rev. Sci. Instrum.*, **21**, p. 991 (1950).
(3) NEEDELS, T. S., and NIELSON, C. E. *Rev. Sci. Instrum.*, **21**, p. 976 (1950).
(4) SHUTT, R. P. *Rev. Sci. Instrum.*, **22**, p. 730 (1951).
(5) BEVAN, A. R. *J. Sci. Instrum.*, **31**, p. 45 (1953).
(6) MILLER, D. H., FOWLER, E. C., and SHUTT, R. P. *Rev. Sci. Instrum.*, **22**, p. 480 (1951).
(7) SHUTT, R. P., FOWLER, E. C., MILLER, D. H., THORNDIKE, A. M., and FOWLER, W. B. *Phys. Rev.*, **84**, p. 1247 (1951).
(8) FOWLER, W. B., SHUTT, R. P., THORNDIKE, A. M., and WHITTEMORE, W. L. *Rev. Sci. Instrum.*, **25**, p. 996 (1954).
(9) SCHLUTER, R. A., and WRIGHT, S. C. *Rev. Sci. Instrum.*, **26**, p. 1053 (1955).
(10) SNOWDEN, M. *Progr. Nuclear Phys.*, **3**, p. 1 (1953).
(11) ALSTON, M. H., CREWE, A. V., and EVANS, W. H. *Rev. Sci. Instrum.*, **25**, p. 547 (1954).
(12) BATSON, A. P., and RIDDIFORD, L. *Proc. Roy. Soc. A.* To be published.
(13) HIBBARD, L. U. *J. Sci. Instrum.*, **31**, p. 363 (1954).