meant we had to move the magnet out quite a considerable amount. So this is the reason why the magnetic field has gone down a little below the others. The rest of the answer is exactly the same as you got from Shutt. We regard the first third of the chamber as a target; this is very loose, I admit; the other 2/3 is the part we actually do the measurements on. Now we feel 40″ is necessary in order to do the measurements with the accuracy that we want.

Peyrou: Since Hildebrand is going to ask me his usual question, I might answer immediately that I don't know why our chamber is exactly two metres long. You can put forward reasonably rational arguments why a narrow chamber is an instrument well adapted to high energy physics. If you are exceedingly rational you could say that the ratio length to width should be of the same order of magnitude as the γ of the centre of mass in the collision of a particle of the primary beam with a proton. This is the first point. The second point is that in the quarrel between small chambers with high field and low field large chambers I believe that the low field large chamber is better as a general purpose instrument, because I believe the kind of information you get from a bubble chamber depends very much on how much you let secondaries make secondary or tertiary interactions as the geometrical mean free path in hydrogen is 4 metre. So any chamber shorter than 4 metre is certainly too short.

O'Neill: In the operation of the British chamber, the arrangement is to be such that the bubble growth is very fast, much less than 1 ms. I would suppose that it would take of the order of 10 to 20 ms for the chamber to go from no sensitivity to full sensitivity; in this time there is a reasonable chance of getting at least one cosmic ray μ meson into so large a chamber. Is there any difficulty, because with this fast bubble growth there is a good chance that some tracks were started in this way much sooner than the beam pulse has been turned on?

Evans: The bubble growth is no faster than in other chambers. The delay between the entry of particles and the flash can be made short.

SOME FEATURES OF CERN HYDROGEN BUBBLE CHAMBERS

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The purpose of this paper is not to describe in detail the hydrogen bubble chambers in existence or projected at CERN. I would prefer to discuss some speculations and describe some experiments that we have performed, most of them in order to foresee the future performances of the CERN 2 metre bubble chamber.

There exist in CERN two hydrogen bubble chambers which have been used with the 600 MeV Synchro-cyclotron, a 10 cm and a 30 cm one. The 10 cm one was built and used in order to acquire experience in the field. The 30 cm one is now finished and produced tracks for the first time at the beginning of May 1959. It will be placed inside a magnet giving a field of 15 000 G.

30 CM CHAMBER

Fig. 1 shows the chamber schematically. The diameter is 32 cm, the depth 15 cm, giving a total volume of 15 l. The chamber body is made of stainless steel. Tempered glass is used for the windows. The gaskets are made of rings of hard copper, which have a circular section, and are covered with indium.

This system of gaskets is used in metal—metal joints as well as in glass—metal joints. These gaskets are very satisfactory. The copper provides a gasket which does not flow and is tight after several cooling and warming cycles; and the indium takes care of possible small scratches. The chamber is expanded by a piston of stainless steel, 11 cm in diameter. The piston movement is forced and not due to the pressure of the liquid. The piston can be demounted without dismantling any part of the chamber inside the vacuum tank.

The temperature of the chamber is controlled by means of a pressurized bath working in closed circuit and transferring heat to a reservoir of hydrogen boiling at atmospheric pressure [1]. The bath sur-

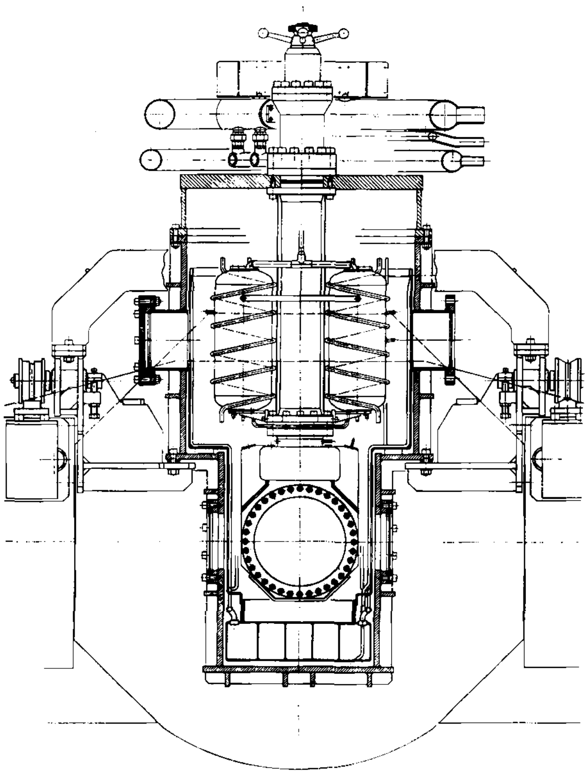

Fig. 1 Hydrogen bubble chamber of 32 cm diameter.

rounds the piston and also the top of the chamber but not the bottom, in order to avoid the formation there of a cold layer. This system of controlling a chamber made of poor heat-conducting material by cooling only the top and letting some convection movements take care of the homogeneity was incorporated for the first time in the CERN 10 cm chamber and has been very successful here and elsewhere.

Another important feature of the chamber is the fact that all the valves are pneumatically operated and remote controlled. All these valves are permanently attached to the top of the vacuum tank from which the chamber itself is suspended. Therefore the chamber can be extracted from the vacuum tank without taking apart any vital part of the piping. The chamber can be disconnected from the control panel and reconnected to it in a short time.

Preliminary results on distortion and bubble counting

The 30 cm chamber has worked recently in a π^+ beam of 250 MeV and 330 MeV given by the CERN Synchro-cyclotron for a $\pi-p$ scattering experiment without magnetic field.

We have measured, using the CERN I.E.P., the curvature of only 13 tracks, so far, therefore no real study of distortions has been made. All that can be said is that the mean radius of curvature measured for these 13 tracks was 41 m and that expected from Coulomb multiple scattering was 45 m. 41 m corresponds to 18 GeV/c in a field of 15 000 G. If measurements with better statistics confirm the preliminary results it is not unreasonable to hope that the maximum detectable momentum, for very high energy particles (with negligible Coulomb scattering), will be at least 40 GeV/c. C. Dilworth of Milan University and D. Morrison of CERN have also made some measurements of mean gap length. They used a projection microscope. The choice of mean gap length as parameter related to ionization was based on the same sort of considerations as are ordinarily used in emulsion techniques. It is probably the parameter which is the least sensitive to differences in bubble growth and illumination, and it can be measured on relatively highly ionizing tracks. The results, here too, are very preliminary and were obtained on the 10 cm chamber as well as on the 30 cm chamber. (In the 10 cm one the tracks are shorter but the demagnification of 1/5 instead of 1/11 in the 30 cm permits the counting of shorter gaps.)

The results are the following. If tracks of minimum ionization are compared in the same frame, the fluctuation of $\bar{g}$ (mean gap length) has a standard deviation of about 7%. If one compares measurements in photographs in different frames but taken with the same operating conditions, the standard deviation is about 10%. No significative gradient of sensitivity in the chamber has been detected so far.

As already stated the results are very preliminary, but even so it is not unreasonable to hope that in medium or large size chambers, gap measurements can become a very useful method for the identification of non-relativistic particles.

Expansion curves—Dynamic load—Velocity of evaporation

Fig. 2 shows typical expansion curves of the 30 cm chamber. They exhibit a pressure curve taken at the bottom of the chamber with a capacity measuring gauge and a curve of the displacement of the piston (measured by a varying capacity device) expressed in

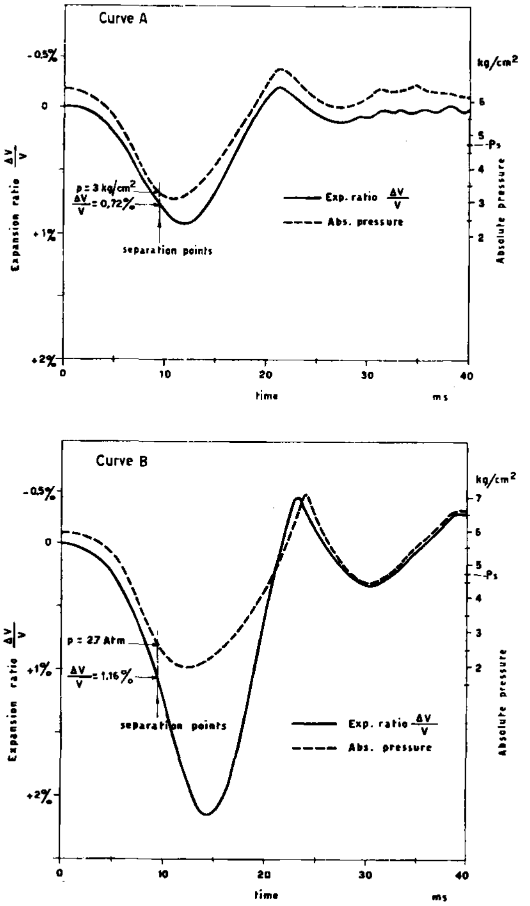

Fig 2 Expansion curves in the 30 cm chamber. Chamber volume 13.4 l. Piston area 104 cm². P_s = vapour pressure at the chamber temperature.

expansion ratio $\Delta V/V$. The curves of (a) correspond to normal operation of the chamber; we operated the chamber and obtained good tracks with an expansion ratio as low as 0.84%, starting from a pressure of 6 atm absolute with a chamber temperature of 26.8° K (vapour pressure 4.7 atm abs.). In the operation corresponding to Fig. 2 (b) the chamber was purposely over-expanded in volume. The overall time, expansion to recompression, is about 20 ms. There is some bouncing of the piston after the recompression; this is due to a damping mechanism which is too elastic; it has no harmful consequence on the performance of the chamber.

From the form of the curves it is possible to draw a certain number of conclusions.

1. The pressure curve flattens out before the piston curve does. This means that at a certain moment a gas pocket is formed whose growth compensates the movement of the piston. Since such a large pocket is not observed in the chamber, it is easy to conclude that it is formed at the piston, in other words, the liquid surface has detached from the piston. Such a detachment has indeed been observed by eye at least in operation of the type of (b) by means of a mirror placed in such a way that it allows us to observe the piston during operation.

2. The two curves allow us, in the time before detachment, to measure the compressibility of liquid hydrogen $dV/dp/V$; the results vary somewhat from 0.2% to 0.26% atm^{-1}. These numbers are definitely smaller than the isothermal compressibility and rather larger than the adiabatic compressibility. It is not known if the difference from the adiabatic compressibility is real or whether it is due to some imperfection in the chamber (leaks around the piston, for example).

3. It is possible from this curve to calculate the dynamic load, based on the following principle. The comparison of the two curves gives the total volume of hydrogen evaporated at a given pressure. One assumes that the dynamic load is equal to the work done in recompressing this volume of hydrogen from the minimum pressure to the vapour pressure or the final pressure of the chamber. (It is not easy to decide which hypothesis should be adopted. Sometimes the pressure curves indicate that hydrogen re-liquifies before the final pressure is reached, sometimes it is the contrary but the results are not very different.) In operation of the type (a), the calculation gives a dynamic load corresponding to the evaporation of 0.5 l of liquid hydrogen per hour for an expansion rate of one every two seconds. Experimentally, we found 0.6 l/h; the agreement is certainly too good for the uncertainty in the calculations, but it shows that this type of calculation can give a reasonable order of magnitude. (No measurement of dynamic load was made with type (b) operation because they were not maintained long enough to be sure that a new state of equilibrium had been reached on the heat exchange between chamber and pressurized bath.)

4. From the type (b) curves it is possible to deduce the rate of evaporation of hydrogen. In type (a) operation it is not entirely sure that the whole surface had detached, but it is almost certain for type (b) operation since the overstroke of the piston is so large.

By measurement of the velocity of the piston when the pressure is stationary, it is found that the rate of evaporation is 0.7 g $\sec^{-1}$ cm^{-2} when the pressure was 2 atm abs., the original temperature of the liquid being 26.8° K (vapour pressure 4.7 atm). There are several things that can be said about this value :

a) It is very uncertain; it does not take into account the fact that leaks at the piston also contribute to flatten the pressure curve, and the actual surface of the liquid may not be the cross section of the cylinder.

b) This figure is very small compared with that deduced from (naïve) kinetic theory of gases, but it corresponds to a heat transfer at the surface of the liquid which is much too large to be due to heat conductivity alone. Therefore it must be due to currents which may very well depend on the previous history of the liquid column in the cylinder (velocity, acceleration). (At the time of measurement this column does not move.)

c) However, *if it is found later that this figure is a correct order of magnitude and does not depend too much on many unknown parameters, it will be useful in planning piston-expanded chambers.*

At first glance, it will seem that the conclusion from our experiments is that chambers should be expanded by pistons of relatively small cross-sections moving at large velocities. In such a case even if detachment occurs too early, the piston could cope with the evaporation and complete the expansion of the chamber. Indeed if it is assumed that the rate of evaporation is a function of the difference p_0-p, where p_0 = vapour pressure of the liquid at equilibrium and where p is the pressure actually existing at the surface, it can be shown that an early detachment of the liquid is not of great importance for the pressure curve. What we call the point of detachment may very well be the point at which the effects of detachment become large enough to be detected. In this case there will be, in fact, a vapour expansion, but the calculated heat load will be relatively small, and very different from a true vapour expansion where mixing of cold and warm gas may occur.

However, there are several arguments against pistons which are too small and too fast (apart from mechanical difficulties) : the velocity may favour an early detachment. The velocity of evaporation may increase with the velocity of the liquid surface.

Particularly in large chambers it is dangerous to have too large velocities, or rather, too large an acceleration. In such chambers the piston may have to be located at a rather large distance from the main chamber volume. Now consider a cylindrical expansion tube of length l, containing a liquid of density ρ, which is accelerated with a certain acceleration γ. This acceleration produces a pressure difference, $\Delta p = \rho\gamma l$ ($\Delta p = 3$ atm for $\gamma = 500$ g, $l = 1$ m) between the ends of the tube and this can cause detachment at the piston. Of course this figure is reduced if the expansion line is a cone, but the effect remains serious.

These considerations may be presented in a slightly different and more general form. The liquid of a chamber gives a certain elastic force which accelerates the liquid in the expansion line and also the piston in the case of chambers in which liquid has to push the piston. Expressing this in mathematical form, one obtains the equation of a harmonic oscillator with a characteristic period which depends on the volume of the chamber, the compressibility and density of the hydrogen, the cross-section and length of the expansion line and a factor which depends on the form of the line. For typical designs of large chambers it is easily found that the period is of the order of 20 msec. It will, of course, be absurd to try to expand the chamber in a time shorter than this natural time. The period corresponds clearly to the time between the beginning and the end of the cycle. It should therefore be noted that the introduction in the expansion line, of parts which are too long for their cross-section may have the most disastrous effects on this time constant.

Vapour expansion trial

We have performed a simple experiment in an attempt to study effects in a vapour expansion line. The apparatus is shown in Fig. 3. A tube of plexiglass 2.5 cm diameter is placed in a transparent Dewar containing liquid hydrogen at 20° K; the liquid H_2 Dewar was itself placed in a nitrogen Dewar. Gaseous hydrogen was liquefied in the plexiglass tube but since plexiglass was a good insulator, it was easy to maintain this hydrogen at a temperature of the order of 28° K. The temperature was measured by a vapour pressure thermometer. Using two Barksdale valves, expan-

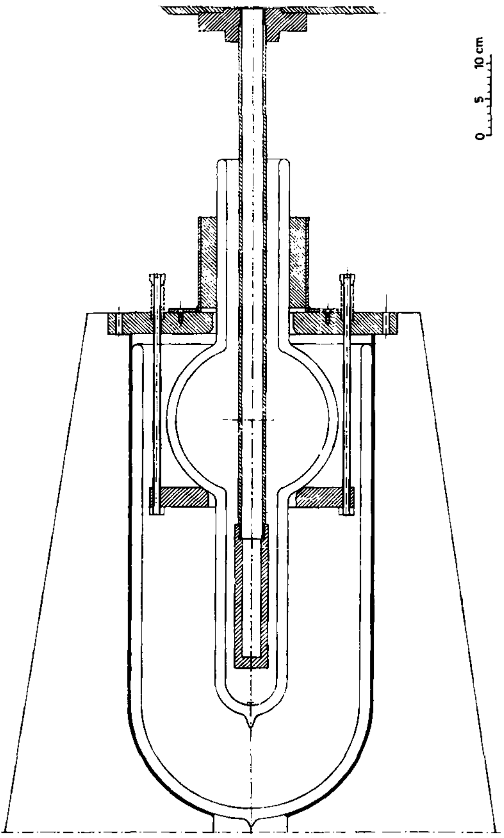

Fig. 3 Apparatus for the study of vapour expansion.

sion-recompression cycles of variable length were made in the plexiglass tube producing a pressure drop of 3 atm, while effects at the liquid surface were observed directly. No violent evaporation at the surface was seen but what was observed was the formation of fog in the gas due to condensation of hydrogen at the moment of expansion i.e. a cloud chamber effect. We were unable to measure the velocity of evaporation at the liquid surface by this method.

What we observed was a slow decrease of the level of the liquid, but this was due to the difference between the amount of liquid evaporated when the chamber was maintained expanded and the amount reliquefied at the recompression i.e. the dynamic load. By integrating over many pulses the amount evaporated per pulse was measured (after correction for the amount liquefied between pulses). It turns out that on this surface of 5 cm^2, the amount evaporated per pulse was 0.05 cm^3 of liquid; the liquid having a temperature of 27.5° K and remaining at 2.5 atm for 12 msec. The amount evaporated was roughly proportional to the duration of the time during which the chamber remained expanded. This figure is very low for vapour expansion system but the expansion was not very realistic since the surface of the liquid was practically not moving.

2 METRE CHAMBER

CERN is building a large hydrogen bubble chamber. This chamber will be located in a special building which can also accommodate another chamber. Beams will be extracted from the PS machine at a point different from the one which will be used for the present experimental area. The new area will be built in such a way that it will allow other types of experiments to be performed there.

The chamber will have a useful volume of $200 \times 60 \times 50\,cm^3$. The total volume of hydrogen will be $\sim$1000 l. The chamber body will be made of stainless steel, cast or welded, the latter type of construction allows the choice of a stainless steel which will not precipitate a magnetic phase at low temperature.

The chamber will have straight-through illumination. Cold safety tanks will be placed at the front and back of the chamber; they will protect the main vacuum from any glass breakage and will contain hydrogen gas during the precooling. One of them contains the illumination lenses.

The vacuum tank will be built in three parts. The central part is a frame of rectangular shape on which the two others are bolted. The chamber hangs from the top of this frame by a system of articulated arms to allow for thermal contraction. The vacuum tank, chamber and cold tanks are themselves attached to a bridge which rests on the magnets during operation but which is supported and can roll along the floor during demounting.

The magnet can be moved on rails, which run along the length of the building. These rails will also be used for opening the magnet. Furthermore, the magnet can rotate on a turntable attached to it so that the chamber can be placed anywhere in the building in any orientation.

There are two points of interest in the magnet design

a) It will incorporate a correcting coil placed partly in the side yoke and partly in the space between the main coils. This correcting coil will allow beams of low energy to enter the chamber without increasing at all the path length of the beam. The coil is such that it does not disturb the main field.

b) A 1/12th model of this magnet will soon be finished. It is well known that this is very difficult due to the problem of scaling the current density. However, G. Petrucci suggested that the model could be constructed if another material other than iron, were taken. Such a material should have a magnetization curve homotetic to that of iron, i.e. it should have the same slope at the start, but should saturate at a lower specific magnetization. It turns out that Monel is such a material and we are constructing a Monel model. As soon as quantitative results on this method are available they will be published.

LIST OF REFERENCES

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DISCUSSION

Dzhelepov: I would like to ask whether you have done some experiments with deuterium in your chamber and what are the results, if you did?

Peyrou: No, we have not used deuterium.

Rosenfeld: Could you just say where the Monel saturates for this model magnet?

Peyrou: B minus $\mu_0 H$ is around 1 000 or 2 000 G depending on Monel. The construction of the model is, of course, not as simple as I said because Monel samples vary widely, so you have to try many to have a homogeneous sample of material and sometimes you have to anneal it before you make the model. But I think it is worth the trouble.

Evans: Can you not get close enough to this by putting less iron in the model than the scale factor?

Peyrou: I must say I am not a magnet expert.

Evans: That makes two of us!

Peyrou: I think this Monel model is a fine idea, but I am not very able to discuss whether there are even better schemes.