A STUDY OF BUBBLE CHAMBER OPERATING CONDITIONS
FOR HOLOGRAPHIC IMAGE RECORDING

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ABSTRACT

Results of a systematic study of operating conditions for holographic image recording in a heavy liquid rapid cycling bubble chamber are presented. We find that the limiting phenomenon is the turbulences generated by the growth and recompression of the bubbles. To minimize this effect it is necessary to operate the chamber at high temperature where the bubble growth is slow. A total of 40 000 useful holograms were recorded in the NA25 experiment at CERN. Typical running conditions were 10 Hz cycling rate, 80 beam tracks per expansion and a bubble density of 95 bubbles per cm.

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1. INTRODUCTION

Soon after it was established that holography is a practical method to record images it was suggested to use holography in bubble chamber image recording [1,2]. The need to improve the resolution of bubble chambers to study short lived particles like charmed hadrons or tau leptons has recently revived the interest in this possibility.

In conventional photography there is a relation between the depth of field and the resolution. For a resolution of $10\text{ }\mu\text{m}$ the depth of field is around $200\text{ }\mu\text{m}$. The need for a reasonable depth of field ultimately limits the resolution which can be obtained in a bubble chamber. In a holographic recording on the other hand the depth of field is related to the coherence length of the laser which can always be made larger than the bubble chamber. The resolution is ultimately limited by diffraction. Theoretically a resolution of $1\text{ }\mu\text{m}$ is possible in small bubble chambers ($\sim 10\text{ cm}$). In a previous publication [3] we have described the first results obtained with the holographic bubble chamber HOBC. These first results revealed an unexpected difficulty which severely limited the data taking rate. This difficulty is connected with the operating temperature which was chosen for HOBC filled with $\text{C}_2\text{F}_5\text{Cl}$ ($\sim 48^\circ\text{C}$). This choice was motivated by the experience gained from the bubble chamber BIBC which was successfully used in NA18 [4] and which was also used for the first holographic tests in a bubble chamber [5]. At this temperature the bubbles grow fast. Tracks entering the chamber at the pressure minimum reach a diameter of $\sim 400\text{ }\mu\text{m}$ at the end of the chamber cycle. The heat left in the liquid after recompression of these bubbles produces local variations of the refractive index which completely spoil the next hologram. At 48°C the dissipation time for these perturbations is of the order of 1 s , thus limiting the cycling rate of the chamber to about 1 Hz . A similar limitation would apply to recording with conventional optics, but high resolution holography is possibly more sensitive to these effects.

We have performed a systematic series of tests to determine the optimal running conditions for a heavy liquid rapid cycling bubble chamber. The results of these tests are presented in the following sections.

The chamber has now completed data taking for the experiment NA25 at CERN. A total of 40 000 holograms were recorded and the analysis of these holograms is in progress.

2. THE BUBBLE CHAMBER AND THE HOLOGRAPHIC RECORDING ARRANGEMENT

The bubble chamber HOBC is a small, heavy liquid, rapid cycling bubble chamber designed for the use of in-line holography [3]. The visible volume is 5 x 6 x 11 cm³. The heat exchanger, the valves and the pressure gauge are at the top of the chamber. The piston is joined to the chamber body via a stainless steel bellow. The active liquid is separated from the piston and bellow assembly by a 1.5 mm thick VULKOLAN rubber membrane. The space between the membrane and the piston is filled with water. This membrane was introduced in order to reduce the number of joints in the active liquid where spurious boiling could occur. The general thermal control of the chamber was found to be very important. It is achieved by two water loops in the chamber body and one loop in the piston. The water comes from a single water reservoir with a temperature which is stable up to a few 10⁻² °C. The chamber is surrounded by an aluminium tank which was heated with electric heating strips to the same temperature as the chamber body.

The holographic recording layout was the same as the one described in ref. [3]. The field lens doublet was replaced by a triplet with the same focal length which improved the resolution at the edge of the field of view.

The distance between the film and the transported image was 4 cm for an event in the centre of HOBC. The magnification is very close to 1. We found that the disturbance caused by the turbulences decreases if that distance is decreased. However, below 4 cm the noise generated by the virtual image becomes very important.

Fig. 1 shows an example of an interaction in HOBC reconstructed from a hologram recorded with this set up.

For most of the data taking a laser delay of 100 µs was used. This produces bubbles of 12 µm diameter and excellent contrast. Fig. 2(a) shows a profile of such a bubble. The plateau in the centre of the bubble

and the sharp edges suggest that the optical resolution is much better than the visible size. For a test with high beam particle intensity the bubble chamber cycling rate was reduced to 3 Hz so that the turbulences from the previous expansion are completely dissipated. Under those conditions good quality holograms with 220 beam tracks per expansion were recorded with a laser delay of 25 μ s. This laser delay corresponds to 6 μ m bubbles, which is at the limit of the optical resolution of the lens system. Fig. 2(b) shows the corresponding bubble profile, and fig. 2(c) shows that under these conditions two bubbles are clearly resolved when they are separated by 10 μ m.

In an attempt to reduce the influence of the turbulences on the hologram we studied a recording technique with a separate reference beam. The layout for this arrangement is shown in fig. 3. In this case the reference beam is not affected by the turbulences. To allow for an easy comparison of in-line and separate reference beam holograms we used a set-up where both types of holograms are recorded simultaneously on the same plate. The same event with the same turbulences can hence be compared with the two recording methods. The test showed that the effect of the turbulences for the two types of holograms was similar. The contrast for 10 μ m bubbles was however better for the in-line holograms. As a result we prefer the very simple in-line holography. This solution has the additional advantage to require less laser power both at the recording and replay of the hologram.

3. BUBBLE GROWTH RATES

HOBC was exposed to a 800 MeV/c π^- beam at the CERN Proton Synchrotron. The beam flux was around 1500 particles per spill of 250 ms. The trigger required a coincidence of 3 scintillators upstream of the chamber and one scintillator downstream. Two proportional wire chamber planes with a 2 mm wire spacing localised the incident track. Holograms were recorded in freon 115 (C_2F_5Cl) at different temperatures and at various laser delays. The measurements of the bubble sizes are summarized in fig. 4. At each temperature the time dependence of the bubble diameter (D) is well described by the expression $D = A t^{0.65}$ (straight lines in fig. 4). The duration of the bubble chamber cycle was 3 ms.

During the data taking run the bubble growth rate was also measured for freon C_2F_6 at 48.5 °C, 51.9 °C and 53 °C (fig. 5). The data are well described by the expression $D = A t^{0.56}$. These measurements were performed with either a 5 ms or a 7 ms long expansion cycle.

The theory of bubble growth is well known [6,7]. A short discussion of it can be found e.g. in ref. [3]. For a stationary bubble the diameter grows with time like $\sqrt{t}$. Our experimentally obtained growth rates for C_2F_6 differ significantly from this $\sqrt{t}$ behaviour. It is possible that this is due to the motion of the bubble under buoyancy forces. Such a motion is clearly visible on the holograms. We expect this motion to be more prominent for a faster expansion cycle. Indeed the acceleration due to the compression and expansion of the bubble chamber is much larger than the acceleration due to gravity. The buoyancy forces are hence more important for a faster expansion. This explains why the deviation from the $\sqrt{t}$ behaviour is observed mainly for the C_2F_6 data for which the shortest expansion cycle was used. If this interpretation is correct the formula of ref. [3] only applies to very small bubbles (say $< 20 \mu m$) where the movement of the bubble is certainly negligible. Fig. 6 compares the measured growth rate with the theoretical expectation for C_2F_6 . It should be mentioned however that the freon 115 used was industrial grade freon which certainly contained impurities, while the calculation was performed for pure freon. However, in spite of this, the agreement between measured and calculated growth rates is excellent.

4. HEAT DISSIPATION TIME

When a bubble is formed and recompressed a certain amount of heat is first extracted and then returned to the liquid. A bubble moves by several bubble diameters between formation and recompression. After recompression of the bubble, there is, for each bubble, a cold and a hot spot in the bubble chamber. Since the refractive index varies with temperature this produces optical disturbances in the liquid which can preclude the recording of any new hologram before these temperature variations have

dissipated. This effect will limit the maximum cycling rate which can be achieved. This limit will depend strongly on the operating temperature of the bubble chamber. To quantify the effect we define the heat dissipation time as the time after which the turbulences produced by a track become undetectable. This quantity was determined at each temperature with a series of holograms with increasing laser delay. The results are shown in fig. 7.

We have compared these dissipation times with a simple model. It is assumed that the bubble leaves a point-like hot (and cold) spot in the chamber. The heat content of this spot dissipates in a spherically symmetric way according to the heat conduction equation:

$$\nabla T = \rho c/k \quad dT/dt$$

We then calculate after which time a light ray going through the centre of the hot spot undergoes a phase shift of less than $\Delta\psi$.

The result is:

$$t = 360/\Delta\psi \quad dn/dT \quad (Q/4\pi k\lambda)$$

In the above equations the definition of the symbols is as follows:

- T = temperature
- t = time
- ρ = liquid density
- c = heat capacity
- k = thermal conductivity
- Q = heat content of the bubble at the end of the expansion cycle
- dn/DT = variation of the refractive index with temperature
- λ = wavelength of light

The straight line on fig. 7 shows the predicted dissipation time for $\Delta\psi = 20^\circ$. The model overestimates the dissipation time at low temperature. This is due to the fact that convection is ignored in the model. At high temperatures the dissipation time is too short for convection to play any significant role, which explains the improved agreement between the model and the measurement.

5. BUBBLE DENSITY

From the discussions above it follows that it is necessary to operate a holographic rapid cycling bubble chamber close to the critical temperature, i.e. "hot". In the beginning, we found it difficult to control the general level of turbulence in the bubble chamber at higher temperature. This problem was solved by surrounding the bubble chamber with an aluminium tank with an insulation between the bubble chamber and the outer tank. The outer tank is then heated to the same temperature as the bubble chamber itself to minimize heat exchanges with the outside world. With this system the general turbulences can be completely suppressed at any temperature.

A more serious problem is that at a higher temperature the bubble density will be lower.

For C_2F_5Cl the bubble density reaches a maximum at a temperature of 48 °C. The decrease of the bubble density below 48 °C is readily understood. Fig. 8 shows a pressure/temperature diagram for C_2F_5Cl . The lines of constant bubble density come closer to the foam limit at higher temperature. Below 48 °C the bubbles grow very fast. As a result parasitic boiling will produce gas at a faster rate than the expansion system expands the volume, thus preventing the foam limit being reached.

Above 48 °C parasitic boiling does not prevent the foam limit to be reached. It is not clear which mechanism limits the bubble density at these temperatures. It was observed that, when the expansion stroke was pushed to the limit, the windows of the chamber were covered with a sparse layer of bubbles. No boiling was observed in the liquid itself. Presumably under these conditions all surfaces on the inside of the chamber produce bubbles but only on the windows is this foam visible. This observation suggests that the foam limit on the surfaces is reached at a higher pressure than in the bulk liquid. If this interpretation is correct then, even for a perfect, parasitic boiling free chamber, there is a limit to the maximum bubble density which can be reached. This limit seems to decrease with increasing temperature. Fig. 9 shows the measured bubble density versus the operating temperature in C_2F_5Cl with the bubble chamber expanding at 10 Hz.

A systematic study of the influence of various operating parameters on the bubble density is difficult because small changes in the expansion stroke can have a considerable influence on the bubble density. It is however clear that a shorter expansion cycle, a higher temperature and a faster cycling rate all reduce the bubble density. The influence of the length of the expansion cycle is probably related to the speed of sound in the liquid. From the measured static elasticity coefficient of C_2F_5Cl at 56 °C we derive a speed of sound of 160 m/s. In HOBC the pressure wave needs about 1 ms to travel between the piston and the top of the chamber.

Therefore one cannot expect a homogeneous pressure in the chamber liquid with expansion cycles of only a few ms.

Fig. 10 shows the influence of the chamber cycling rate on the bubble density. For this test the chamber was expanded during 2.6 s every 12 s (to simulate typical running conditions of the CERN SPS). Measurements of the temperature with platinum gauges in the chamber body show this decrease in bubble density is related to an accumulation of hot liquid at the top of the chamber. This decrease of bubble density with higher cycling rate can be reduced with improved heat exchangers at the top of the chamber and consequently reduced parasitic boiling.

There is clearly a conflict between the conditions which are needed to avoid the turbulences on one hand and a high bubble density and a high cycling rate on the other hand. Table 1 describes different operating conditions for HOBC which have been used in actual data taking.

6. NUMBER OF BEAM TRACKS PER EXPANSION

Another important aspect of holography is its potential to accept a large number of tracks in a given bubble chamber expansion. When the hologram is replayed only a slice of the volume a few mm deep is in focus at a time. In each slice one can hence accept the same number of tracks which would otherwise have been stored in a conventional photograph. In a hologram the maximum number of tracks which can be accepted is not limited by the general confusion of the overloaded picture but by the reduction in

contrast due to the general noise level. Tracks that are out of focus do not confuse the image but produce noise. In addition each track produces some turbulences in the next expansion. This effect also gives rise to noise in the hologram. At a very low cycling rate where the latter effect is certainly negligible we have obtained well contrasted images with up to 220 incoming beam tracks per expansion. Table 1 also lists the maximum acceptable number of beam tracks under several operating conditions in HOBC. AT 10 Hz, where most of our data were taken, the number of tracks has been varied between 40 and 100 per expansion. We observe a very fast degradation of the picture quality and contrast in this range going from excellent for 40 tracks per expansion to unacceptable for 100 tracks per expansion. This suggests that the limitation to the number of beam tracks per expansion comes mainly from the turbulences left over from the previous expansion rather than from the total amount of information recorded on the hologram. At 20 Hz we obtained good quality holograms with 40 tracks per expansion.

7. CONCLUSIONS

The tests and the data taking for NA25 as well as the analysis of the holograms so far have shown that holography is a useful and practical method to record bubble chamber images. Setting up the holographic recording system or handling the holographic film did not present any particular problem.

The main advantage of holography lies in the practically unlimited depth of field. For a 10 cm chamber a resolution of 6 μm has been obtained over the full 6 cm depth of the chamber. For holographic recording it is important to run the bubble chamber "hot" in order to reduce the variations of the refractive index of the liquid due to the local variations in temperature produced by the growth and recompression of the bubbles.

Running HOBC filled with freon C_3F_8 at a temperature of 53 °C and with a repetition rate of 10 Hz, we obtained a bubble density of ~ 95 bubbles cm^{-1} . The number of beam particles was typically 80 per expansion. With

these running conditions we accumulated a total of 40 000 holograms with particle interactions and this completed the data taking of the first holographic bubble chamber experiment.

We are convinced that with minor improvements HOBC could run at 20 Hz with the same bubble density as achieved now at 10 Hz.

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REFERENCES

- [1] W.T. Welford, Appl. Opt. 5 (1966) 872.
- [2] J.H. Ward and B.J. Thompson, J. Opt., Soc. Am. 57 (1967) 275.
- [3] A. Hervé et al., Nucl. Instr. and Meth. 202 (1982) 417.
- [4] E. Ramseyer et al., Nucl. Instr. and Meth. 201 (1982) 335.
- [5] M. Dykes et al., Nucl. Instr. and Meth. 179 (1981) 487.
- [6] M.S. Plesset and S.A. Zwick, J. Appl. Phys. 25 (1954) 403.
- [7] Bubble chambers, Aleksandrov et al., Indiana University Press (1967).

TABLE 1

Operating conditions used in rapid cycling high resolution bubble chambers

Bubble chamber	Liquid	Temp.	Optics	Cycling rate (Hz)	Resolution (μm)	Tracks/expansion	Bubble density (cm^{-1})	Flash delay (μs)
HOLEBC	H_2	29 °K	Convent.	30	20	15	80	70
BIBC	C_3F_8	43 °C	Convent.	5	30	10	290	15
HOBC	$\text{C}_2\text{F}_5\text{Cl}$	48 °C	Hologr.	1	12	40	200	3
HOBC	C_3F_8	53 °C	Hologr.	10	12	80	95	100
HOBC	C_3F_8	53 °C	Hologr.	20	12	40	65	100
HOBC	C_3F_8	53 °C	Hologr.	3	6	220	100	25

FIGURE CAPTIONS

- Fig. 1   Example of an interaction in HOBC reconstructed from a hologram. The picture corresponds to 2 mm in space. The bubble size is $\sim 10 \mu\text{m}$.
- Fig. 2   Bubble profiles obtained from a reconstructed bubble image with a CCD camera scan line. One division corresponds to $9 \mu\text{m}$ in space. (a) Bubble obtained under normal running conditions with a $100 \mu\text{s}$ laser delay. (b) and (c) Bubbles obtained with a $25 \mu\text{s}$ laser delay. The upper line in each of these figures corresponds to the saturation of the camera.
- Fig. 3   Optical layout used to compare the merits of in-line and two-beam holographic recording.
- Fig. 4   Bubble diameter versus growth time at different temperatures in $\text{C}_2\text{F}_5\text{Cl}$ measured in HOBC. The straight lines are a fit to the data with the expression: diameter = $A t^\alpha$ with $\alpha = 0.65$. These measurements were performed with a 3 ms expansion cycle.
- Fig. 5   Bubble diameter versus growth time at different temperatures in C_3F_8 measured in HOBC. These measurements were performed with a 5 or 7 ms expansion cycle.
- Fig. 6   Growth rate constant A for $\text{C}_2\text{F}_5\text{Cl}$ at different temperatures. The constant A is defined by the relation: bubble radius = $A \sqrt{t}$. The solid line is a prediction based on the theory of Plesset and Zwick as explained in ref. [3].
- Fig. 7   Heat dissipation time for bubbles in $\text{C}_2\text{F}_5\text{Cl}$ as a function of the operating temperature. The dissipation time is defined as the time after which the effect of the heat of the recompressed bubble is not observable anymore. The line is a prediction from a calculation explained in the text.

FIGURE CAPTIONS (Cont'd)

- Fig. 8   Thermodynamic diagram for C_2F_5Cl (freon 115). The dashed lines represent lines of constant bubble density. The lines closer to the foam limit correspond to the higher bubble density.
- Fig. 9   Bubble density as a function of the temperature in C_2F_5Cl with 20 expansions at 10 Hz. This graph is only indicative since several other parameters influence the bubble density.
- Fig. 10   Bubble density in C_3F_8 at 53 °C as a function of the repetition rate. The bubble chamber was operated during 2.6 s every 12 s.

Fig. 1

(a)

(b)

(c)

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Bubble density in $C_3 F_8$ at $53^\circ C$
as a function of the repetition rate

Fig. 10

Fig. 9