CERN-EP/82-28

March 4th, 1982

PERFORMANCE OF THE HOLOGRAPHIC BUBBLE CHAMBER HOBC

A. Hervé, K.E. Johansson, P. Lecoq, P. Olivier, J. Pothier,
L. Veillet, and G. Waurick
CERN, Geneva, Switzerland

S. Tavernier^(*)
Brussels, Belgium

ABSTRACT

The small holographic heavy liquid bubble chamber HOBC has been used in particle beams at the CERN PS and SPS. Under realistic data taking conditions bubble diameters of 12 μm and bubble densities around 200 per centimetre were obtained. The greatest difficulty was to obtain stable running conditions at high repetition rates and high beam fluxes.

Submitted to Nuclear Instruments and Methods

(*) Bevoegdverklaard navorser, NFWO, Belgium

1. INTRODUCTION

Several authors have mentioned that the holographic technique could be used to register particle tracks produced in bubble chambers [1-3]. The striking advantage over classical optics lies in achieving an excellent spatial resolution without sacrificing the depth of field.

Interest in spatial resolutions of a few micrometers is motivated by the short lifetime of charm particles, typically a few 10^{-13} s. For a detailed study of the production and decay mechanisms it is a great advantage to register the decay of these particles by direct observation.

The first holographic recording of bubble chamber tracks was done at the CERN-SPS in 1981 [4]. In a small bubble chamber filled with freon one obtained a spatial resolution of 8 μm over a depth of field of around 10 cm was obtained. The bubble density was around 300 per centimetre.

The bubble density as well as the two track resolution is an important factor to obtain a good pattern recognition. In a heavy liquid like freon, it is usually much easier to obtain a high bubble density, say, $200 - 400 \text{ cm}^{-1}$, than in a light liquid like hydrogen.

The small, heavy liquid bubble chamber HOBC was built for the NA25 experiment [5], the main aim of which is to determine the total charm cross section at different incident momenta. The charm signal is very much enhanced by using a muon trigger, which will result in a relatively small number of holograms to study.

In section 2 the test at the CERN PS will be described, in section 3 the results of the run at the CERN SPS will be discussed and section 4 contains the summary and the conclusions.

2. THE FIRST TESTS AT THE PS

2.1 The experimental arrangement

The experimental arrangement is schematically shown in Fig. 1. The incident beam was defined by three scintillation counters, and for the trigger to the camera and the laser, a fourth scintillator counter situated downstream of HOBC was also used. Normally a rather narrow well defined beam was used, which simplified the scanning of the holograms.

The negative beam had a momentum of 1 GeV/c and contained practically only pions, which at this momentum were minimum ionizing. The intensity of the beam fulfilling our beam criteria was typically 100 per spill, which had a duration of 300 ms.

2.2 The bubble chamber

The holographic bubble chamber, HOBC, is a small (2 l) heavy liquid rapid cycling bubble chamber designed for the use of in-line holography. It is a see-through chamber with two high quality optics windows in BK7 (Fig. 1 and 2).

The photographed chamber volume ($5 \times 6 \times 11 \text{ cm}^3$) is joined via a conical section to the 200 mm diameter stainless steel bellows^(*) (Fig. 3). One of these has already been cycled more than 15 million times. The expansion cycle is 5 ms long. The chamber is closed by a piston, inside which a heat exchanger is fitted for the circulating water.

The heat exchanger, a filling valve, a safety valve and a pressure gauge are placed at the top of the chamber. The chamber pressure is regulated by a simple feedback loop using the expansion motor.

The chamber is surrounded by a vacuum tank which has three main purposes:

- To insulate the chamber from convection and thus allow working closer to the foam limit to increase the bubble density;

(*) Manufactured by Calorstat, Arpajon, France

- To be used as a safety enclosure if propane is used later;
- To be part of the camera system so that the film can be brought nearer the beam plane.

The film plane is situated 12.5 cm from the centre of the fiducial volume. It is sucked onto a five faces capstan, which is fixed on the vacuum tank (Fig. 1). The useful part of the film has the same size as the cross section of the bubble chamber liquid ($11 \times 5 \text{ cm}^2$).

2.2.1 Determination of the operating conditions

The operating temperature was chosen to obtain the maximum bubble density.

Fig. 4 (the thermodynamic diagram for freon-F115) shows the minimum expanded pressure which could be obtained in the bubble chamber as a function of temperature. Below 48°C this pressure is far from the theoretical foam limit. As the temperature increases, the limit gets closer to the foam limit, and above 48°C it follows it closely.

The explanation is that below 48°C the minimum expanded pressure is limited by the growth of parasitic boiling (these parasitic bubbles grow faster at lower temperature, as do the track bubbles). Above 48°C the expansion is fast enough to overcome the parasitic boiling, and the minimum expanded pressure is determined by the hottest point in the chamber, where the foam limit is reached.

With a faster expansion or a cleaner chamber the optimal temperature for maximum bubble density would be displaced towards lower temperatures. However, above 48°C the bubble density decreases slowly with increasing temperature.

At the beginning of the test it was difficult to produce high-resolution holograms, even without expanding the chamber, because of the movement of the liquid due to natural convection. However, by slightly stratifying the chamber a perfect optical background was obtained. The chamber was therefore operated in this unusual condition, keeping the bottom of the chamber 0.3 - 0.4 degree cooler than the top. In this

condition, we obtained very good results up to 10 Hz cycling rate at low beam flux (600 particles per second). The running conditions are summarized in Table 1.

2.3 The holographic arrangement

The bubble chamber was designed to allow the maximum flexibility for the optics. Direct illumination is possible through two optical windows covering an optical volume of $11 \times 5 \text{ cm}^2$ by 6 cm in depth.

After some tests on an optical bench, where both the in-line and the two-beam geometries have been tested, the in-line (or Gabor type) holographic set-up was preferred for the following reasons:

- i) It is very simple to adapt to a small bubble chamber of the HOBC type;
- ii) The set-up for the scanning machine is also very simple;
- iii) The required laser power is a minimum for both the recording (about 2 mJ for a 50 cm^2 hologram) and the replay of the holograms (1 mW with an optical magnification of 5, which gives a total magnification of about 100 on a TV screen);
- iv) The resolution in the HOBC geometry at 12.5 cm distance from the high-resolution target (USAF 51 Chart) was better than $4 \mu\text{m}$. This distance between the film plane and the HOBC centre was chosen as small as possible because previous tests showed a dramatic deterioration in resolution at increasing distances [6];
- v) The contrast, is very high, better, for instance, than for conventional pictures. In addition, it can easily be enhanced on the replay machine by very simple suppression of the background with a spatial filter.

The optical set-up for the first tests with the bubble chamber in a particle beam is shown in Fig. 1. The laser is an excimer laser (the amplifier medium is the excimer gas XeCl) producing 10 ns ultraviolet pulses (308 nm) with an energy of 200 mJ at a frequency up to 30 Hz. This

laser pumps a dye laser filled with Coumarin-307 in order to select the wavelength of 514 nm fitting the argon line for the replay system, with a maximum output energy of 15 mJ. In fact, the dye amplifier was obscured to limit the output energy to 3 mJ only, which was enough to expose the film at a density of 1.3. The film, Agfa 10E56 emulsion on a 170 μm polyester base with antihalo coating, was sucked onto a metallic capstan. Exposed at a density of 1.3 the noise was quite similar to that of 10E56 holographic plates and the signal-to-noise ratio was excellent [7].

Fig. 5 shows a photograph of a reconstructed hologram. The bubble diameter is 12 μm and the bubble density is around 180 per centimetre.

3. THE RUN AT THE SPS

3.1 The experimental arrangement

The incident beam was defined by a system of scintillation counters and was constrained to lie within a diameter of 45 mm to match the bubble chamber window.

An interaction trigger was obtained by demanding in the system of scintillation counters situated downstream of HOBC, a charged particle multiplicity greater or equal to three.

The incident beam consisted of 360 GeV/c protons. The intensity was varied between $2 \cdot 10^5$ and $2 \cdot 10^6$ particles per spill, which had a duration of 1.8 s.

The beam was equipped with a fast kicker magnet, (rise-time $\sim 15 \mu\text{s}$) which could remove the beam before and after the useful bubble chamber sensitive time for a total of 5 ms. This was essential in order to remove the effect of early incoming particles, which would give rise to very large bubbles, completely dominating the picture and ruining the visibility of the very small bubbles associated with the triggered interaction. The removal of the beam was, however, not sufficiently efficient to eliminate the problem with early incoming particles. This will be discussed in more detail in section 3.4.

Two beam proportional chambers, which had 1 mm wire spacing, were used to determine the entrance co-ordinates in the bubble chamber for the incident particle that caused the trigger. This information was also available for film strips developed during the run and which were immediately inspected.

3.2 The bubble chamber operation

The bubble chamber running conditions were very similar during the run at the SPS and the test at the PS. With the fast beam kicker magnet, very short particle bursts could be produced matching the bubble chamber expansion. The length of the bursts was typically 50 - 100 μ s. However, one important problem emerged when we combined high beam fluxes (up to 2×10^6 particles per second) and a repetition rate of 10 Hz. Although the bubbles are rapidly recompressed (around 20 ms), the heat generated by this recompression diffuses slowly in the bulk liquid. These heat channels, which had a refraction index different from the surrounding liquid, disturbed very much the hologram taken at the following expansion. In Figs 6 - 9, it is shown how tracks (or track remnants) look between expansions, by using laser delays up to 100 ms. The photos are direct prints of in-line holograms. Once the bubbles have disappeared, what is seen is the refraction index differences due to thermal gradients.

After 400 ms there is almost nothing remaining; however, these holograms have been taken with few tracks per expansion (around four). If the beam flux is increased to, say, 40 particles per expansion, then the nice background which is needed for high-resolution holograms is definitely spoilt.

In these circumstances we chose to run the chamber with 500 to 900 ms between expansions to ensure the quality of the holograms taken, because their "scannability" was considered the most important point.

3.3 The holographic set-up

The first holograms showed that the picture quality was very dependent on the turbulence in the chamber. As it is practically impossible to

obtain pictures with a few microns resolution through a turbulent medium with any optical system (classical or holographic), extensive work was done to define operating conditions for the bubble chamber with the maximum liquid stability. In addition, the effect of the turbulences was analysed in order to define an optical set-up minimizing their influence. The turbulences affect the illuminating wave as it travels to the object, causing a non-uniform illumination of the optical field owing to amplitude variations. The object wave is also distorted, both in amplitude and in phase. Finally the reference wave going through the medium also suffers from phase and amplitude variations, causing an unpleasant background and additional sources of noise at the reconstruction.

However, a possible compensation of the variations of the object and of the reference beam exists under certain conditions. A given bubble diffracts useful information in a forward cone, which defines an area on the hologram the diameter of which depends on the distance of the film to the bubble. This area also gives the useful section of the reference beam for this bubble. If this area can be made small compared to the mean turbulence size, both the object and the reference rays are affected by the same phase shifts and the interference pattern is not modified by the turbulences. More details are given in the literature [8,9]. The obvious solution is to reduce the distance of the object to the hologram. As this was not possible in our case due to mechanical constraints, we decided to use a relay lens of very good quality and to take a hologram of the image of the bubble rather than of the bubbles themselves. In order to keep the reference beam parallel a field lens system was added approximately in the plane of image formation of the first lens; with this configuration the constraint on the optical quality of the field lens is a minimum as only a small part of it is used for a given bubble. In fact the field lens system was made of two converging lenses with relatively large radius of curvature in order to minimize aberrations due to prismatic effects on the edges of the field. The idea to use an afocal system was already mentioned in previous publications [10,11]. The new optical set-up is shown in Fig. 10. With this system the distance from the centre of the HOBC to the hologram has been artificially reduced from 12.5 cm to 4 cm. This system of lenses had a magnification of 1.1.

3.4 Data taking and results

The use of the afocal system dramatically improved the picture quality, especially when the chamber liquid was not perfectly stable. Very good images with sharp bubbles and an impressive contrast have been obtained. With a laser delay of 3 μs , the reconstructed bubble size measured with a microscope was around 12 μm (full width above the background). The intrinsic resolution of the system is probably better than 10 μm , as the bubbles appear round-shaped and sharp (Fig. 11). Fig. 12(a) shows a bubble profile projected on a CCD camera. One division corresponds to 12 μm in space. Two bubbles are easily separated at a distance of about 10 μm (Fig. 12(b)). The contrast is better than 70%. The slope of the profiles suggests that the limiting resolution is better than the bubble size as the top is flat and the edges are sharp (Fig. 12(c)). With a delay of 1 μs , 7 μm bubbles were seen, but not so sharp and with much less contrast; at this level the quality was probably limited by the relay lens which has a frequency cut-off of about 6 μm .

The 3 μs delay was finally chosen for the data taking. Under these conditions more than 10000 holograms with an event trigger and 1100 holograms with a muon trigger have been taken with a bubble density of 200 bubbles cm^{-1} for the beam tracks. These holograms will be used for the first physics study of particle interactions using the holographic technique.

As explained in section 3.2 the expansion rate of the bubble chamber had to be limited to 1.4 Hz, because of the time needed to evacuate the heat left in the liquid after the bubble recompression, which was causing turbulent channels. A series of holograms were taken at a high particle flux in order to test the storage capability of holograms. Unfortunately we were working in a slow extracted beam and even when the beam was kicked out, some particles from the beam halo went through the chamber. At fluxes in excess of 10^6 particles per second, the probability was high of having a few very old tracks (1-2 ms). In the vicinity of these tracks the image quality becomes poor as can be seen in Figs 13 and 14. In Fig. 14 an event with 12 μm bubbles is hardly visible close to a 200 μm track. However, more than 100 tracks have been stored on some holograms. In this case the image quality is still very good if all the tracks have bubbles smaller than 50 μm . We just noticed a slight degradation of the signal-to-noise ratio.

4. FUTURE PLANS

To improve the cycling rate, we now plan to study and test a certain number of ideas to bring the sensitivity of the experiment NA25 to the desired level.

- Modifications of the bubble chamber and its operating conditions will be made to find more favourable working conditions: e.g. an expansion system with an added membrane, higher working temperature and active mixing of the liquid. The higher working temperature, in particular, is expected to provide some improvement. At higher temperatures the bubble growth is slowed down and less heat is produced by the recompression of these smaller bubbles. In addition, the "old" tracks which now limit the maximum acceptable flux in the chamber will be smaller and hence less disturbing. (See Appendix).
- A different holographic technique based on a separate reference beam should be tried out in an attempt to reduce the sensitivity to the turbulences and, possibly, to accept a larger number of tracks in the bubble chamber. Tests with two-beam holography have until now yielded rather disappointing results, but work in this direction should continue.

5. SUMMARY AND CONCLUSIONS

More than 12000 holograms of particle interactions have been registered in the heavy liquid holographic bubble chamber HOBC during the first run of the NA25 experiment. Under realistic data taking conditions bubble diameters of 12 μm and bubble densities around 200 per centimetre were obtained.

The heat produced by compressing very large bubbles limited the useful repetition rate to around 1.4 Hz. As is shown in the appendix there are good reasons to believe that the repetition rate could be much improved by changing the operating conditions.

An advantage of holography is to have the maximum resolution in the full volume of the bubble chamber, which allows a gain in sensitivity by a factor of 10 compared to classical optics as 100 tracks per hologram look reasonable.

Finally, the experience with the analysis of NA25 holograms indicates that holograms are not much more difficult to analyse than classical optics high-resolution pictures. The optics of the scanning and measuring machine must, however, be carefully set up in order to exploit the maximum quality of the holograms, which is in general very good.

These results show that holography is a very powerful technique which can be used in very high resolution particle physics experiments.

ACKNOWLEDGEMENTS

We are indebted to A. Guiard-Marigny, D. Güsewell, A. Minten, L. Montanet and E. Pauli for their continuous interest and support. We would also like to thank J.L. Bénichou, A. Didona, G. Merighi, K. Rogers, H. Stiquel and J. Vernois for their competent contribution to the construction and running of HOBC.

We also want to recognize the importance of the advice given to us by W. Birr and A. Lefrançois in the design stage of HOBC.

We appreciate H. Drevermann's dedicated work in setting up the scanning equipment, which was essential for this project. The contributions by H. Anders and K. Geissler are also very appreciated.

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] F.R. Eisler, Nucl. Instr. and Meth., 163 (1979) 105.
- [4] M. Dykes, P. Lecoq, D. Güsewell, A. Hervé, H. Wenninger, H. Royer, B. Hahn, E. Hugentobler, G. Ramseyer and M. Boratav, Nucl. Instr. and Meth. 179 (1981) 487.
- [5] Bari-Brussels-CERN-Mons-Paris-Strasbourg-Vienna Collaboration, Proposal to study the production of charm and bottom particles using a holographic bubble chamber, CERN/SPSC/80-120, SPSC/P 155.
- [6] P. Lecoq and P. Olivier, Proc. Meeting on the Application of Holographic Techniques to Bubble Chamber Physics, Rutherford Laboratory, 1981, RL 81-042 (1981) 94.
- [7] H. Royer, Proc. Meeting on the Application of Holographic Techniques to Bubble Chamber Physics, Rutherford Laboratory, 1981, RL 81-042 (1981) 80.
- [8] H.T. Yura, Appl. Opt. 12 (1973) 1188.
- [9] J.W. Goodman, W.H. Huntley, Jr. D.W. Jackson and M. Lehmann, Ap. Phys. Lett. 8 (1966) 311.
- [10] P. Lecoq, Proc. Meeting on the Application of Holographic Techniques to Bubble Chamber Physics, Rutherford Laboratory, 1981, RL 81-042 (1981) 175.
- [11] R. Bizzarri, The use of an afocal optical system to image holographic bubble chambers, CERN/EP/EHS/PH 81-21.
- [12] M.S. Plesset and S.A. Zwick, J. Appl. Phys. 25, 403 (1954).
- [13] D. Güsewell, private communication.

Table 1 - HOBC operating conditions

- Filling: C_2F_5Cl	F115
- Operating temperature	48 °
- Static pressure	26 bar
- Vapour pressure	16 bar
- Expanded pressure	6 bar
- Liquid density	1.25
- Piston stroke	1.25 mm
- Expansion cycle duration	5 ms
- Bubble density	200 to 220 cm ⁻¹
- Laser delay	3 µs

FIGURE CAPTIONS

- Fig. 1 A schematic layout of the beam counters (S1-S4) and the optical layout at the PS.
- Fig. 2 View of HOBC showing the dimensions of the visible volume.
- Fig. 3 Cut view of HOBC showing the general arrangement and the position of the expansion.
- Fig. 4 Thermodynamic diagram for freon F115.
- Fig. 5 Photograph of a reconstructed hologram taken at the CERN-PS. The photo measures 2.7 mm and the short proton track is 300 μm long. The bubble diameter is 12 μm and the bubble density is around 180 per centimetre.
- Fig. 6 Hologram taken after a laser delay of 160 μs .
- Fig. 7 - " - 2.5 ms.
- Fig. 8 - " - 10 ms.
- Fig. 9 - " - 100 ms.
- Fig. 10 Optical set-up for the data taking with the afocal system.
- Fig. 11 Typical event with 12 μm bubbles. The picture length is 2 mm. The diffuse square is a fiducial cross out of focus.
- Fig. 12a Projected bubble profile. One division corresponds to 12 μm in space.
- Fig. 12b Two bubbles separated by 10 μm .

Fig. 12c Two bubbles separated by around 35 μm .

Fig. 13 Event with 12 μm bubbles close to an old 80 μm track.

Fig. 14 Event with 12 μm bubbles close to an old 200 μm track.

APPENDIX

Heat dissipation in a bubble chamber

Below we estimate the influence of the bubble chamber operating temperature on the time needed to dissipate the heat produced by the creation or recompression of a bubble.

The present calculation is based on the theory of bubble growth by Plesset and Zwick [12]. We ignore the effect of bubble movement due to buoyancy forces as well as the effect of the variation of pressure during the cycle. Detailed calculations performed by D. Güsewell [13] show that these effects do not change these results significantly. Under these assumptions the time dependence of the bubble radius is given by :

$$r = A \sqrt{t}$$

$$\text{where } A = 2 \sqrt{3/\pi} \sqrt{k \rho c} \left(T_{\infty} - T_b \right) / h \rho'$$

- k : thermal conductivity of the liquid
- ρ : density of the liquid
- c : specific heat of the liquid
- h : heat of vaporisation
- ρ' : density of the gas
- T_{∞} : temperature of the liquid
- T_b : temperature in the bubble : at this temperature the vapour pressure equals the expanded pressure.

From the formula it is easy to see that the growth rate must decrease if the temperature is increased. The term $T_{\infty} - T_b$ (ΔT on Fig. 4) decreases rapidly with increasing temperature. Another, but less important reason for this decrease is the variation of $h\rho'$. Table 2 gives the calculated growth rate constant A for different temperatures. All predictions have been multiplied by 0.83 to make them agree with the experimentally observed value at 48° C. For comparison the growth rate constant for hydrogen at 29° K is also given. The physical constants of C_2F_5Cl and H_2 used in this calculation are given in Table 3. For the actual calculation the variations of the physical properties of the liquid with temperature have been taken into account.

From the growth rate it is possible to predict the size and the heat content of a bubble at the end of the expansion cycle, i.e. after 1.5 ms. This should approximately be equal to the amount of heat which must be dissipated. If a bubble is grown and later recompressed a certain amount of heat is first extracted from the liquid and then returned. In the process a net amount of heat, of the order of $V \Delta p$ is produced. This irreversible heat is typically an order of magnitude smaller than the heat content of the bubble.

The bubble diameter grows at a speed of $\sim 100 \mu\text{m/ms}$. At the time of recompression the bubble has a diameter of several hundred micrometers. The heat is thus not returned at the same point as it was extracted. Convection will then further separate the hot and the cold liquids. The dissipation time will thus be the time needed to dissipate the total heat content of the bubble. In table 2 we see that this heat content decreases dramatically with increasing operating temperature. Increasing the temperature from 48°C to 60°C for example reduces the heat content of bubbles with a factor 200. With decreasing heat content also the time to dissipate the heat in the liquid will decrease. Our estimates indicate that the heat dissipation time decreases even faster with increasing temperature than the heat content. Consequently, at higher temperatures the heat dissipation time should be orders of magnitudes smaller than at 48°C .

We conclude that in order to cycle the bubble chamber at around 10 Hz, it should operate at a temperature between 55 and 60°C .

Table 2

Heat content and bubble growth rate of different temperatures.

Liquid :		A [cm/ $\sqrt{s}$]	heat content [cal]	
C_2F_5Cl	48° C	0.35	1.2	10^{-5}
	55° C	0.10	5.0	10^{-7}
	60° C	0.046	5.9	10^{-8}
	65° C	0.023	8.6	10^{-9}
H_2	29° K	0.095	9.3	10^{-8}

Table 3 : Some relevant physical properties of
hydrogen and C_2F_5Cl (Freon-115)

		H_2 (at 29° K)	C_2F_5Cl (at 50° C)	units
thermal conductivity	k	$3.31 \cdot 10^{-4}$	$1.07 \cdot 10^{-4}$ (25° C)	$cal \cdot cm^{-1} \cdot s^{-1} \cdot K^{-1}$
density saturated liquid	ρ	$5.6 \cdot 10^{-2}$	1.15	$g \cdot cm^{-3}$
heat capacity liquid	c	4.5	0.32	$cal \cdot g^{-1}$
evaporation heat	h	77	18	$cal \cdot g^{-1}$
density saturated gas	ρ	$8.5 \cdot 10^{-3}$	0.14	$g \cdot cm^{-3}$
variation refractive index dn/dT		$4.07 \cdot 10^{-3}$	$1.14 \cdot 10^{-3}$	$^{\circ}K^{-1}$

Fig. 1

Fig. 2

Fig.3

Fig. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 9

Fig. 10

FIG. II

a)

b)

c)

FIG. 12

FIG. 13

FIG. 14