PHOTONICS APPLIED TO NUCLEAR PHYSICS: 1

EUROPEAN HYBRID SPECTROMETER WORKSHOP ON
HOLOGRAPHY AND HIGH-RESOLUTION TECHNIQUES

Strasbourg
Council of Europe
9-12 November 1981

GENEVA
1982
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ABSTRACT

The purpose of this Workshop was for nuclear physicists and photonicists to exchange views and to establish efficient ways of collaboration. Photonics is the study of the methods of measuring, transforming and transmitting information by means of light. One of the most important techniques of photonics is holography. Its three-dimensional recording capacities have been observed for some years, but it is only recently that photonicists have developed the means to use them effectively in other fields. The results can be applied to nuclear physics and bubble chambers where high-quality three-dimensional recording systems are required. Discussions during this Workshop were mainly concerned with the high-resolution program for the European Hybrid Spectrometer (EHS) and the possibilities offered by the application of holography to the Rapid Cycling Bubble Chamber (RCBC) or smaller devices used in conjunction with a modified EHS set-up, modified by adding e.g. streamer and high precision wire chamber. The advantages and disadvantages of photonics for a future nuclear physics program have also been reviewed.
ORGANIZING COMMITTEE

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PREFACE

In contrast to the previous workshops of the EHS held in the antiquity and calm of the old town of Vézelay, we move this year to the splendour of the Council of Europe in Strasbourg. The meeting has expanded to bring together the physicists of the EHS and the optics experts of the European Photonics Association in order to better understand the limits of high-resolution techniques in bubble chamber physics. The study of charmed particle production and decay in liquid hydrogen represents a most exciting and challenging programme for the EHS in the coming years. The search for ever shorter lifetimes and hence even better resolution has led us to consider leaving the "comfort" of classical optics in favour of holography. It is therefore very good to find that our photonics friends are already comfortable in dealing with holograms and can teach us a great deal about how to proceed.

I would like to thank at the outset the Council of Europe for providing such a splendid venue for our meeting and for arranging such a successful marriage between the two physics communities. Thanks, of course, go to the photonics specialists for sharing their considerable knowledge and experience with us, and to the Conference secretariat staff, Mes M. Cobut, I. de Tournemine, S. Pfister and F. Vermeille, for working so hard to make the meeting a success. Finally, many thanks to the CERN Scientific Reports Editing Section and the Composition and Printing Group for producing these proceedings so quickly after the Conference.

So now: what went on ... you are invited to read the proceedings.

Nicole KURTZ (Chairwoman)
for the Organizing Committee
PROGRAMME

9 November 1981

Chairman L. Montanet
Speakers M. Grosmann
M. Boratav

10 November 1981

Chairman M. Cresti
Speakers N. Kurtz
S. Reucroft

OPTICAL PROBLEMS

Speakers P. Meyrueis
G. Vanhomwegen
F. Lamy

Chairman R. Bizzarri
Speakers A. Hervé
P. Lecoq
E. Johansson
H. Leutz

Chairman L. Voyvodic
Speakers R. Sekulin
R. Bizzarri
K. Geissler

Chairman P. Smigielsky
Speakers C. Fisher
R. Newport
D. Gisewell
E. Miranda
H. Royer
H. Bjelkhagen
R. Bizzarri

11 November 1981

SPECTROMETER PERFORMANCE

Chairman H. Leutz
Speakers A. Poppleton
G. Zimmerlé
B. Pilgroms

11 November 1981

Chairman H. Wenninger
Speakers E. Johansson
S. Holmgren
A. Hervé

Chairman J. Sandweiss
Speakers N. Doble
L. Montanet

ANALYSIS PROBLEMS

Speakers G. Ciapetti
J.R. Lutz
H. Drevermann
K. Geissler
V. Petersen
P. Meyrueis
P. Liégeois

12 November 1981

ACTIVITIES IN OTHER FIELDS

Chairman P. Meyrueis
Speakers R. Prypuniewicz
H. Annoni
F. Pouyat
H. Wenninger

Chairman H. Royer
Speakers L. Voyvodic
J. Sandweiss
V. Eckhardt
A. Larkin

ROUND TABLE DISCUSSION
of technical problems and developments
in the field of high-resolution holography
as applied to the future physics programme

Chairman R. Prypuniewicz
P. Meyrueis

CLOSING SESSION

Chairman M. Cresti
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ADDRESS

J.P. Massué
Scientific Counsellor to the Parliamentary Assembly of the Council of Europe and
Chief of Division for Higher Education and Research, Council of Europe

Mr Chairman, Ladies and Gentlemen,

In December 1980 the European Photonics Association was created under the sponsorship of the Parliamentary Assembly of the Council of Europe. We are assembled for a workshop jointly organized by CERN and the European Photonic Association on photonics applied to nuclear physics and specifically on the problem of the hybrid spectrometer and the association of holography with high-resolution techniques. I would first of all like to welcome this co-operation between CERN and the Council of Europe.

I should like to take this opportunity to remind you of the links between the European Photonics Association and the Council of Europe in this context.

The Council of Europe is an intergovernmental organization with 21 member states and 25 states taking part in the activities in the field of culture and education. Briefly, we have all Western European countries involved in these activities.

The main structure of the Council of Europe consists of:
- the Parliamentary Assembly composed of 170 parliamentarians and the same number of alternates appointed by their national parliaments;
- the Committee of Ministers which works on the level of the Ministers of foreign affairs or of their deputies. To serve both structures, there is the General Secretariat with a staff of 800 persons.

The Parliamentary Assembly is composed of specialized Parliamentary Committees such as those for science and technology, education and culture, political affairs, legal affairs, environment, etc.

In 1970, the Parliamentary Assembly adopted an Order with the aim of:
i) strengthening scientific cooperation in Europe;
ii) creating links between parliamentarians and scientists with the aim of assisting the parliamentarians in their political decision making.

To meet such requirements different scientific working parties were set up in specific fields with multidisciplinary views. The European Photonics Association, for example, was created in this framework.

To meet the second goal, a Joint Committee between parliamentarians and scientists was created (The European Joint Committee on Scientific Co-operation) composed of parliamentarians from the different parliamentary committees, scientists from the scientific working parties, and observers from the national authorities competent in the field of scientific research.

To set up mechanisms to assist the parliamentarians in their political decision making, European parliamentary hearings have been organized regularly. The principles of the hearings are very simple; when politicians have to take decisions on specific topics, we try
to provide them, in a minimum time, with information on a global scale, taking into account the different points of view of the social groups concerned. This information is provided through questions raised by a parliamentary jury to a group under challenge composed of 4 sub-groups: i) representatives of governments, ii) technical and research organizations, trade unions, industries, iii) independent experts, iv) representatives of international organizations.

You will recall the European Parliamentary hearing held in Toulouse on 11 March 1978 on the specific needs of Europe in the field of remote sensing, organized with the cooperation of EARSeL (European Association of Remote Sensing Laboratories).

At the intergovernmental level, the work programme of the Council of Europe in the field of tertiary education and research is established on the advice of the Standing Conference on University Problems (CC-PU). This body is unique in grouping together higher officials from Ministries of Education or Universities and academic representatives. It has observers from the other European organizations working in the field. The target group consists of students, teachers and researchers.

The programme has three parts:

i) Analysis, studies and conferences

The aims of this part of the programme are to furnish Ministries of Education and academic authorities with studies and analysis relevant to their major concerns and also to organize creative sessions, work seminars, and conferences, with participants of parties interested in the development and use of intellectual capital.

ii) Academic mobility

The aim of this activity is to contribute towards the freedom of movement between institutions of tertiary education and/or research by improving mobility information and by reducing legal, administrative and financial obstacles.

iii) European programme for the development of post-graduate training

The main objective of this part of the programme is to encourage European institutions of tertiary education and research to co-operate in the improvement of post-graduate curricula by a flexible, pragmatic, and continuous adjustment of training programmes to further the advancement of knowledge and to meet the needs of, and new opportunities offered by, our society.

This co-operative effort should stimulate positive developments regarding teaching methods: mobility of teachers, researchers and students, quality of training programmes; the process of innovation; the communication between educational institutions and society and the pooling of international expertise: the process of technology transfer and transfer of know-how; student guidance; development aid; information to decision-makers and educational planners; and improvement of the cost/efficiency ratio.

This programme is carried out in the form of intensive courses and European workshops.

I wish you a successful meeting and hope that your Strasbourg Workshop will lead to a development of future European scientific co-operation.
INTRODUCTION TO PHOTONICS AND HOLOGRAPHY

M. Grosmann
Université Louis Pasteur de Strasbourg

These new terms cover a group of advanced technologies based on the specific properties of the interaction between light and matter that have been discovered since the development of lasers. Electronics uses electricity to process information: photonics performs the same functions, but uses light instead of electricity. Photonics can be said to cover all the methods, processes or systems which serve of study, measure and transform or transmit by means of light. The photon devices which have resulted from fundamental and applied research in this field over the last ten years or so cover a comparable range of application areas to that of electronics - mechanical engineering, medicine, avionics, telecommunications, biology, metrology, quality control, hydraulics, computers, botanical science, textiles, remote sensing, pneumatics, aerospace, etc. The list is too long to give in its entirety, but for our present purposes there are four types of significant products: lasers and their accessories, optical fibres and their accessories, data acquisition, processing and display systems and photovoltaic and solar systems.

- LASERS, which originally were mainly used for scientific applications, are rapidly coming into use in many other fields. The first of them is holography, which has opened up a number of flourishing markets. It is a means of producing images in three dimensions and, because of its metrological properties, is now highly sought after in advanced mechanical engineering (the fuel tanks of the Ariane rocket were tested by holography). The second significant application of lasers was in machining: they have advantageously replaced conventional processes for cutting out cloth and sheet metal and for welding or machining new materials. Some of the many industrial applications of lasers are developing very fast: an example is automatic data read-out, which is becoming widespread in the United States. Finally, lasers have become components in a wide variety of systems, from laser surgery to telemetry and military guidance systems.

- OPTICAL FIBRES are another line along which photonic has developed, and are all the more promising as their characteristics make them indispensable to the economic development of the technically advanced countries. They are in fact the only known way of coping with the growth in large-scale telematic exchanges (picture, sound, alphanumeric, coded signals, etc) and offer other important advantages (insensitivity to electromagnetic disturbance, very small line losses and cheap, abundant raw material enabling the use of other rarer materials such as copper to be avoided).

- DATA ACQUISITION AND DISPLAY SYSTEMS are another area in which photonics has made great advances. Progress in this field centres mainly on video tubes and liquid crystal thermographic systems, where simple applications afford economic thermic images. In the field of photon cameras, so called CCDs (charge coupled devices) make it possible to obtain images thanks to their matrix mounting. Prototype black and white and colour television cameras exist which have the advantages of being highly miniaturised (five to ten times smaller than ordinary cameras) and more economical; in addition, the image which they produce has
the advantage of being easily digitalised and used as a metrological or form recognition
criterion. There are very many possible developments (surface control, quality control of
cloth etc) and one of these, the video-disc, is beginning to reach the general public. The
general trend is to connect computers up to photonic data acquisition systems so as to
achieve automatic operation whereby a machine can be controlled or a phenomenon understood.
The use of these processes yields end products of higher quality at minimum cost.

1. **LASERS**

   **Section 1: Lasers - basic principles**

1. **Définition**

   The word "laser" is made up of the first letters of the term "Light Amplification by
   Stimulated Emission of Radiation". We shall not go in detail into the theoretical principle
   of lasers, but merely outline some aspects which will make it easier to understand the prin-
   ciples of their technological applications.

**Radian emission and radiance**

   The principle of stimulated emission which enters into the definition of the laser is a
   microscopic principle which is not visible directly but can be arrived at by a fairly complex
   theoretical analysis (1). There is an equivalent definition of the word laser, viz: "Light
   Amplification by Super Emission of Radiation", based on a macroscopic process (radian em-
   ision) which is easily observed and affords an easier understanding of laser principles.

   Since the end of the 19th century, physicists have agreed that different lamps (or light
   sources producing luminous energy while consuming energy of a different kind) can be compared
   with each other in terms of their "radiance". Radiance can be represented on a graph where
   the x axis is the energy consumed per unit of time by the light source, and the y axis is the
   light energy produced. For example, choosing units and a scale appropriate to the axes, Figure
   1 represents the radiance curves of an incandescent lamp (broken line) and a fluorescent
   tube (continuous line).

![Figure 1](image)

(1) The usual definition is based on the principles of quantum mechanics, according to which
electrons gravitate around atomic nuclei, and have energies with can only take definite
values: these are the so-called "quantum" energy levels. An electron move up to a higher
level if it receives a quantity of energy (heat, light etc). The electron will tend sponta-
ecessarily to return to its original level by liberating the extra energy accumulated during the
upward movement. This energy is liberated in the form of light emission, governed by the equation:
"Energy = Planck's constant x emission frequency". The characteristic of the laser derives from
our ability to trigger coherent emissions (of the same frequency).
Within a given range, the relationship is a straight line whose slope characterises the efficiency (and therefore to some extent the quality of the lamps). If we move outside the range considered, on the right, by increasing the power, the lamp tends to fail (the filament is burnt out or the lamp explodes, etc). Moving to the left, on the other hand, if we decrease the power the lamp emits almost no light. It should also be noted that these lamps (the only ones which existed in 1960) emit in the same manner in every direction, and consequently the energy they radiate is scattered throughout the entire space surrounding them and dims very rapidly as one moves away. The quantity of energy received per unit of surface decreases by $1/r^2$ when $r$ (the distance away from the lamp) increases.

**Super-radiance**

In 1960 it was discovered that if particular lamps can be constructed in such a way that they are able to receive a great deal of power without burning out or exploding, the radianc curve takes on a different form: above a given threshold, the output is considerably improved (Figure 2).

![Figure 2](image)

The zone in which output is markedly improved is called the "super-radiance" zone to distinguish it from the zone in which normal behaviour occurs. This super-radiance cannot really be used to manufacture lamps which are more economical than traditional lamps, because the particular design needed to prevent the lamp from burning out implies a radianc which is 10 or 100 times less than that of an ordinary lamp (even in the super-radiance region, a laser consuming 100 Watts normally emits far less than 1 Watt).

**Properties of super-radiant sources**

Although they are not advantageous from the energy standpoint, super-radiant sources are of considerable interest: their luminosity (or "brilliance") is found not to be uniform but to increase with increasing length of the lamp in the direction considered. This phenomenon consequently makes it possible to obtain a directionality of light emission which is "intrinsic" to the lamp and not due (as in the case of headlights, electric torches, projectors, etc) to the use of lenses and mirrors. In other words, the longer the lamp, the more brilliant it will be in the direction of elongation. If we take a tube of length 10 m and diameter 1 mm as a super-radiant lamp, its maximum brilliance will be concentrated in an angular cone whose vertex is more or less equal to $\frac{4}{L} = 10^{-4}$ radian, or approximately 1/3 of a minute of arc. If we illuminate the moon with this source, the spot on the moon might have
a diameter of $300,000 \times 10^{-4} = 30$ km; if we shine it on a wall 1 km away, the spot will have a diameter of 10 cm: thus the light energy emitted is situated within a very narrow cone.

**Design principle of the laser**

A tube 1 mm in diameter and 10 m long is virtually impossible to handle. The idea therefore arose using a property of mirrors to make it easier to operate: if the super-radiant source is placed between two parallel mirrors perpendicular to its axis, the light from point A of the source is reflected by the mirrors and passes back and forth across the super-radiant medium many times. It is found that, when this light emerges at the end of N crossings, it behaves like the light emitted by an analogous super-radiant source N times as large.

For the light to be usable, it must emerge outside the space enclosed by the mirrors. This can be achieved by swiftly withdrawing one of the mirrors, to produce a "pulse laser". An alternative method is to silver a mirror only partially (eg 99%); this produce a "continuous laser" which releases a constant beam 100 times less powerful than the "internal" beam, but 100 times more directional than if there were no mirrors.

**Figure 3**


Medium containing the atoms to be excited (Pérot Fabry cavity):

a. CO$_2$ + N$_2$ + He gases; or
b. crystal (ruby, YAG, etc).

Atom excitation source:

c. electronic flash coupled with (b) or
d. electric discharge coupled with (a)
e. fully reflecting mirror
f. partially reflecting mirror
g. concentration lens.

Let us take the case of a material medium excited by any means (pumping). This medium is placed in a Pérot Fabry interferometer, i.e. simply between two mirrors one of which is semi-transparent. We have then built a simple laser, and the laser emission will occur along the axis of the interferometer.

There are very many ways of achieving a laser emission. The medium can be solid, liquid or gaseous. The pumping mode may be optional, electrical or chemical.
Qualities of laser emission

The wave is highly monochromatic, and will be concentrated by means of a lens at a quite specific focal length, unlike other sources (heated filament or flash) where the radiation is polychromatic.

2. IMAGES AND IONICS

1. Image of an object: visual information transmission chain

Figure 1 represents a man looking at a fir tree on which the sun is shining. Let us try, by means of this example, to analyse and understand what happens when a "spectator" or "observer" "sees", "looks at" or "observes" a "scene" or "illuminated object" by means of one or more "lamps" or "light sources".

![Figure 1](image)

The illuminated object - in this case the fir tree - reflects light from the light source - in this case the sun - towards the observer - in this case the man walking along. Thus the latter "sees" the object through the intermediary of the light emitted by the source, modified by the object before it reaches his eyes. The observer's visual system (eyes) then transforms the light into nerve signals which are conveyed to the brain.

The whole complex of processes which take place when we look at something can therefore be represented as a chain transmitting something which, for the time being, we shall call "information" and which can be represented schematically as in Figure 2.

![Figure 2](image)

If the observer were to look through an "apparatus", such as spectacles, binoculars or a television system, the information transmission chain would be somewhat more complicated.
Thus the process whereby the image of an object which we look at is formed, is a process of transmitting information along a chain.

2. "Reproduction" of an image

The process of formation of a visual image which we have just examined has a number of consequences.

First of all, the information about the object has to move along the chain from one link to another. Each link can transmit to the following link all or only part of what it has received from the preceding one. Information about the object can be lost, but cannot be acquired in the course of the transmission process. On the other hand, information about other objects can be added by one link and passed on to the next. This is what we call "noise", because it is irrelevant to the picture of the object in question. For example, a car driver may be troubled at night by the image of the dashboard instruments reflected in the car's windscreen. The "windscreen" link adds the noise "image of dashboard instruments" to the information about the road seen through the windscreen, this information being transmitted by the link "light passing through the windscreen".

We can also try to cut a link out of the chain. If we can then find a way of getting to the link below the missing link the same information at that transmitted by that link before it was removed, none of the following part of the chain will notice its absence. If this is only approximately done, the lower part of the chain will notice that a link is missing but will not be greatly troubled by its absence.

In practice, one heavily used link is the link "light reaching the eye". If we can make light which, when it reaches the eye, produces on the retina an identical "image" to that produced by the object, the observer will believe he is looking at the object.

We employ this process so often that we call the systems which perform this operation "images" and do not distinguish, in language terms, between the "image" of the first type described and that of the second. One corresponds to the direct acquisition of information about the object, and the other to indirect acquisition.

3. Quantitative description of light

In order to know whether the explanation of a phenomenon is correct or false, it is necessary to quantify it in order to test the results of the deductions permitted by the hypothesis. Quantification of the description of light has exercised many generations of physicists, because the phenomena are not only microscopic but very rapid and very complex. Fortunately, they can be reduced to a few very simple basic phenomena.

Light waves can be characterised by the values, at various points in space and at different times, of the electric field of light. This field is expressed in volts/metres. For a long time it was difficult to measure it, for it does not have a more or less fixed value except in very small volumes (10^{-21} m^3 - one ten-thousandth of a millimetre across) and for very short periods (10^{-15} seconds, or one thousand million millionth of a second), but the problem has now been more or less solved. It has been found that the usual light waves are always very complex, but are made up of large numbers of very simples waves which are called plane waves, and which we shall described in greater detail in the
following paragraph. Whether simple or complex, each light wave can be represented by the table of values of its electrical field at every point and every moment of its existence. This table of values of field $\mathbf{E}$ at various points in space (co-ordinates $x, y, z$) and at various instants $t$ will be called $\mathbf{E} (x, y, z, t)$. Thus, instead of locating points in space by their cartesian co-ordinates $x, y, z$ we can also locate them by the position of the vector $\mathbf{r} = \mathbf{OM}$ linking each of these points $M$ with co-ordinates $x, y, z$ to an origin $O$. In this case, the table is written $\mathbf{E} (\mathbf{r}, t)$; it is easier to construct than the precedings one, since it takes the shape of Figure 4, but it contains neither more nor less information than the preceding table.

![Table E(r, t)](image)

3. **PLANE WAVES, MOIRÉ AND INTERFERENCE**

1. **Plane waves and the principles of superimposition**

   It would be impossible either to complete or to read the preceding quantitative table within the space of a human lifetime. In practice it has been observed that a simpler description can be obtained by assuming that the real distributions used in optics can be regarded as fairly approximately equal to superimpositions of a few "plane waves" whose electric fields can be represented by the equation:

   $$E_{\mathbf{r}} = E_0 \exp(-i(K \mathbf{r} - \omega t)).$$

   The numerical values $E_0, K$ and $\omega$ determine the position of the plane wave throughout the whole space $(\mathbf{r}, t)$, theoretically to infinity. This is therefore much more concise than the table $\mathbf{E}(\mathbf{r}, t)$ envisaged above. A typical non-plane wave can be obtained on the basis of a fairly small number of plane waves. A few tens, or at most a few hundreds of numerical values are sufficient to describe any real field. Consequently, its properties and the laws governing propagation and interaction with matter can be studied within a reasonable time scale relative to a human lifetime, ie over not too long a period (since the physicist cannot be paid by society), but not too short a period either (since otherwise all the
problems would be solved in less than a day, and the physicist would be out of work).

2. Moiré effect and reference

When plane waves of the same amplitudes and frequencies and similar wave vectors are superimposed, interference occurs (as we learnt in our younger days, and as is readily observable in soap bubbles). There is no need to go back over the theories of Fresnel or Young at this point, but it may be as well to note that these phenomena can nowadays be very usefully approached from a slightly different standpoint than the conventional one - that of the moiré effect.

Classical "interference fringes" are in fact traces on observation planes of four-dimensional moiré fringes constituted by waves in $R_4$. This has educational, and also heuristic, value. Its application to holography by way of "holodiagrams" makes it considerably easier to record holograms.

4. HOLOGRAPHY

1. Phenomenology of holograms

From the standpoint of the non-specialist user, a transmission hologram is a window which records the light falling on it. A scene visible at one moment through this window can be reproduced at a later moment. Under optimum conditions, the real scene would be indistinguishable from the reconstituted virtual scene. Instead of operating the appliance in the transmission mode, it can also be made to operate in the reflection mode. The reflection hologram then behaves like a recording mirror. In both the transmission and the reflecting modes, it is possible to make the reconstituted scene appear on the observer's side of the hologram. The three-dimensional image is then real, though it remains intangible because it consists only of light.

It does, however, make a striking impression on the observer and is a very convenient way of carrying out dimensional measurements. For example, the distance between the two ears can be measured by placing a centimetre rule in the relief image of the head.

2. The principle of recording and restitution of a hologram

a. Recording

![Diagram of hologram recording process]

b. Restitution

![Diagram of hologram restitution process]
3. Qualitative explanation of the process

During recording, the light (reference beam R) coming direct from the laser, and the light reflected or diffracted by the object (object beam O) interfere on the photographic plate. In other words, their superimposition creates four-dimensional interference fringes which, when projected on to the surface of the plate during recording, appear as light and dark areas. If the object beam is screened, the reference beam illuminates the plate uniformly and vice versa.

During restitution, the reference beam illuminates the plate uniformly; however, if the plate has been suitably developed (i.e., the image reversed), there appear in its plane silver grains which cut off the beam at those points where there were interference fringes during the recording. Immediately below the plate plane (transmitted light) or on that plane (reflected light), the light is consequently the same during recording and restitution.

The laws governing the propagation of light (Maxwell equations) enable us to state that if it is the same in the same plane at two different moments for the same beam (reference beam R), it will be the same beyond that plane.

Therefore, the light beyond the developed, reversed plate illuminated only by the reference beam (or indeed only by the object beam) will be the same as during the recording. Thus, during restitution, the same light beams are found beyond the plate as during recording, although only one beam is used for illumination.

All this can be summed up as follows:

"If the developed plate is illuminated with the reference beam, the object light beam is reconstituted; conversely, if the plate is illuminated with the object beam, the reference beam is reconstituted".

4. Quantitative explanation

We shall consider the simplest case, where both the object and reference beams are plane waves.

\[ \mathbf{R} = \mathbf{E}_R \exp(-i(\mathbf{k}_R \cdot \mathbf{r} - \omega_R t)) \]

\[ \mathbf{R} = \mathbf{E}_O \exp(-i(\mathbf{k}_O \cdot \mathbf{r} - \omega_O t)) \text{ and/or } \omega_R = \omega_O = \omega \]

What happens in practice

In practice, the waves will be more complex; that is, they can be considered as superimposed plane waves and will normally have to be written:

\[ \mathbf{E}_p = \sum_{m} \mathbf{E}_m \]

\[ \mathbf{R}_p = \sum_{n} \mathbf{R}_n \]

and the calculation described below will simply have to be repeated by the addition of as many plane waves as are necessary to describe the real wave.

The illuminations produced by the reference wave and the object wave respectively on the plate plane are:

\[ i_O = \mathbf{E}_O \mathbf{E}_X \quad i_R = \mathbf{R}_R \mathbf{R}_X \]
The illumination of the hologram produced by their superimposition is:

\[ i_H = (\bar{O} + \bar{R}) (\bar{O} + \bar{R})^X \]

Multiplication gives:

\[ i_h = i_o + i_r + \bar{O}.\bar{X} \bar{R} + \bar{O}.\bar{R}^X \]

If the plate is properly exposed, the darkening will be proportional to the illumination. If we then develop it and reverse the image, the transparency of the developed plate will be:

\[ T = i_h = i_o + i_r + \bar{O}.\bar{X} \bar{R} + \bar{O}.\bar{R}^X \]

If we illuminate the plate treated and positioned in this way as for the recording by the reference beam, the transmission will be the product of the illuminating light and the transmittance of the plate.

\[ \bar{R} T = \bar{R} i_H = \alpha \bar{R} + \beta \bar{O} + \gamma \bar{O}^X \]

or

\[ \alpha = i_o - i_r \]
\[ \beta = i_r \]
\[ \gamma = R^2 \]

5. Immediate analysis

It is immediately apparent that we have three transmitted beams (and also three reflected ones). If we are to be able to see them distinctly, they must be quite separate geometrically, otherwise the eye will see them superimposed and be unable to distinguish one from the other satisfactorily. In order to maximise the reconstitution of 0 (proportional to \( i_r \)), relative to \( R \), which is proportional to \( (i_o + i_r) \), \( i_r \) must be maximised relative to \( i_o \) during recording. It is fairly easy to discuss \( O^X \) as the "real image" and this can be treated as an exercise.

In practice, the different plane waves must be summed and account must be taken of the non-linearities of the emulsions, as a result of which \( T = f(i_H) \) instead of \( T = i_H \).

In practice, however, there is no point in reversing the plate. As the interference fringes recorded are very small and microscopic, the transmitted (or reflected) light is "diffracted" and is the same for a reversed plate as for its original image. (The demonstration of this statement was made a century ago and is called the Babinet theorem).

Further, it is implicit in what we have already said that, in order to record the interference fringes between the object beam and the reference beam we must ensure that their trace on the photosensitive plate does not move during the recording. This means that the beams, and thus the object, the laser and the plate must be fixed relative to each other to within one tenth of a wavelength; whereas in photography, therefore, the object, lens and plate must be fixed relative to each other to within one tenth of a millimetre during exposure, in holography the object, laser and plate must be fixed to within one tenth of a micron. So while a "snapshot" in photography means an exposure of, for example, one milimetre, in holography it means one microsecond or less.
6. **Precision and resolution criteria**

There are two stages in evaluating the precision and resolution of the holographic image.

**Stage 1**: this stage takes account of factors which limit resolution and are independent of recording conditions. Resolution is limited by the finite limits of lens aperture and the hologram itself.

**Stage 2**: this stage takes into account factors bound up with the recording conditions: non-linearity of photosensitive materials, vibration and movement, and fluctuations in coherence during recording.

The analysis can be described in terms of resolution or of modulation transfer functions. The analysis of modulation transfer is normally very suitable. Without going into detail (some practical examples may be given by way of an exercise), let me point out that resolutions of a few microns are nowadays fairly easily obtainable, but that the greater the analysed volume is, the bigger the hologram surface must be because of the transfer of information from the three-dimensional distribution inside the object to the two-dimensional distribution to the place. However, if one is interested only in certain particular points on the object space examined, it is possible by means of existing technologies to determine their positions, and changes in their positions, with great accuracy (as high as one thousandth of a micron).

7. **The problem of restitution with a reference beam different from the recording reference beam**

If the restitution beam is different from the recording beam, everything we have so far discussed is theoretically invalidated. However, if the differences are very small, the above conclusions preserve approximate validity. In other words, the restituted three-dimensional images of the objects are distorted. These distortions are known as aberrations.

The most common aberrations are due to wavelength differences between the recording and restitution beams. Numerical values are easily derived from basic formulae. Summing up, it can be said that resolution decreases sharply when the recording is non-linear and the restitution conditions differ from the recording conditions. There are, however, a few fortunate exceptions to this general rule which can be used to advantage.

5. **BUBBLE CHAMBER HOLOGRAMS**

1. **Introduction**

The recording and restitution sources, and the recording materials, must of course be selected in accordance with the objects to be holographed. A few aspects of the use of bubble chambers are discussed below.

2. **Dimensional aspect**

If plates measuring 9 x 12 cm are being explored, it is a condition of good resolution that the volume studied should be less than 1 cubic decimetre. That volume may, however, not be cubic: it can be of more or less any shape, e.g. a flattened or elongated cylinder. Surface recording materials up to 1 metre square can be used for larger volumes, but the cost then rises considerably.
3. Quality of the recording laser beam

The recording laser must be able to expose the plate during a short triggering period. This is not a problem. Note that continuous lasers can be used to record holograms during periods of the order of one picosecond, taking advantage of the fact that if the time and coherence length are short, fringes will reform only in keeping with those times and lengths. This affords an economic means of performing ultra-rapid cineholography. Resolution is currently poor, but could be improved fairly easily.

4. Quality of the restitution beam

It is relatively easy to obtain a restitution beam with the same geometrical properties as the recording beam.

On the other hand, when the recording beam is pulsed, it is difficult to obtain a continuous restitution beam with the same wavelength. Using a coloured laser beam is expensive, as is a high-resolution monochromator spectograph and correcting aberrations by image processing. A detailed analysis is needed to optimise the elements which are genuinely indispensable for the actual problem one is attempting to solve.

6. CONCLUSION

This brief survey of the conditions needed for the recording and restitution of holographic information on images of particle paths in bubble chambers makes no claim to be exhaustive. It may, however, clarify some ideas and facilitate the colloquy discussions. Certainly, it is very easy to make a hologram, much easier than most people think; recording and restituting photonically - the most interesting part of a very rapid phenomenon - is more difficult and requires a sound knowledge both of photonics and of the phenomenon studied itself.
WHAT MAKES THE HEPHY*) RUN?
(An introduction to High-Energy Physics)
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ABSTRACT
My aim, in this short report, is to explain to those unfamiliar with high-energy physics, why (and, to some extent, how) experiments are done in our field. I shall try to show how interesting particle physics can be, and why it is worth while to invest so much effort in undertaking more and more complicated experiments -- effort on the part of our home institutions in money and facilities, and also on the part of the physicists themselves, whose professional life is generally far from being easy-going.

1. WHY HIGH-ENERGY EXPERIMENTS?

If the aim of physics is to explore the laws governing the behaviour of matter (whatever it is!), particle physics is an ever-moving field on one of its frontiers, much as cosmology is the corresponding domain on the opposite frontier. The limits of our field change with the years, because the notion of “particle” changes with the experimental techniques available. We know that to study an object of dimension \( R \) we need a tool whose size does not exceed this dimension. For us the tool itself is a particle of given energy which we use as a probe. If this probing particle has a momentum \( p \), the associated wavelength is

\[
\lambda = \frac{h}{p} \quad (h = \text{Planck constant}).
\]

This wavelength roughly defines the size of the probing tool. We can thus write (at high energy) a relation between the size \( R \) of the object we want to study and the energy \( E \) of the probing particle:

\[
E \sim \frac{1}{R}.
\]

This simple relation shows why we need more, and more powerful, particle accelerators to study the most intimate structure of matter. As an example, we can explore the structure of an atom \( (10^{-7} \text{ cm}) \) with a particle of energy \( 10^{-5} \text{ GeV} \) (1 GeV is roughly the mass energy of a proton), whilst we need \( 10^3 \text{ GeV} \) to "see" the structure of atomic nuclei, and 100 GeV to prove that the nucleons are made out of smaller (point-like?) objects called "quarks."

*) HEPHY: Familiar name for a High-Energy PHYSicist, a seasonally migratory biped, generally living in funny places such as Hamburg and Geneva, subsisting mainly on sandwiches, and very fond of gathering (specially by night) along accelerator tunnels. Can easily be recognized by its dishevelled garments and very pale skin. Has the surprising ability of currently writing on blackboards and, to some extent, of speaking (but with a very limited vocabulary of a few hundred words).
2. FROM ATOMS TO QUARKS

The history of particle physics is a continuous search for and discovery of new particles, some discoveries being completely accidental (as was the case, for example, for the muon in 1936) and most of them preceded by a theoretical prediction.

The leptons (or weakly interacting particles) are one of the particle families and, to some extent, the most puzzling one. They seem to be point-like particles, grouped in successive generations of pairs, one member of which is always charged (the best known being the electron) and the second always neutral and probably massless (the neutrino). Although an extensive experimental program has been devoted to the understanding of their properties, many questions concerning the leptons simply remain unanswered: nobody can explain today why the leptons exist (they are completely unnecessary except for the first generation); how many generations there are; why each charged lepton has a massless partner specifically related to it and not to the others, etc. No doubt one of the thrilling prospects of future high-energy physics will be to answer these questions and many others concerning the leptons.

The hadrons (strongly interacting particles) constitute the second large family, of which the proton and the neutron are the members most familiar to laymen and also the only ones existing as perfectly stable entities in nature (the neutron is unstable when free and stable when bound inside an atomic nucleus). By the way, their stability is a necessary condition to the existence of matter (hence of the author, the reader, and the paper on which these things are written), although this stability might well be an approximation.

Actually in particle physics the word "stable" is used with a much larger acceptation: all particles decaying through weak and electromagnetic interactions (see below) are called stable. Their mean lifetimes are generally larger than $10^{-18}$ s. We shall see that one of the reasons why we are interested in holographic techniques is directly related to such lifetimes.

Coming back to the history of hadrons, it could be said that one of the main topics in high-energy experiments during the last 30 years was to create hadrons (the higher the energy, the higher the masses of the hadrons discovered) and then to try to understand their properties and production mechanisms. The first-discovered hadrons were the most "stable" ones (because of the detection techniques used); then as the techniques improved, a host of excited-state hadrons (called resonances) decaying via strong interactions (i.e. in about $10^{-23}$ s) began flooding the particle market -- from a few units in the 50's, we are getting close to 100 nowadays. It may look like fun to discover a new particle every three months, but physicists have simplicity-loving minds, and this wild proliferation of particles was not felt to be at all satisfactory unless one could find some elementary scheme underlying such a complex spectroscopy.

A giant step was taken in this direction when, in the early 60's, Gell-Mann, Ne'eman and Zweig proposed independently to use some basic unitary symmetry principles to classify the hadrons. One of the consequences of this theory was that the hadron spectroscopy behaved as if the strongly interacting particles were all built out of three elementary entities, called "quarks". But it was not until much later that even the fcrefathers of the quark theory could believe that the quarks were anything else than mathematical tools. One had to wait until high-energy technology was able to probe the nucleons' structure (which corresponds to distances less than $10^{-14}$ cm or energies larger than 200 GeV) to see that the
hadrons had actually an internal structure and that their constituents had all the expected properties of the quarks. Today, belief in the quarks is universal, even if they have some unconventional properties such as fractional charge, even if their number is increasing steadily, even if we are unable (up to now) to observe them as free particles. To summarize the situation regarding the structure of hadrons, the most widely accepted ideas are the following.

There are six species (we say flavours) of quarks which are considered as being the elementary building blocks of matter; we have indirect evidence for five of them, called the up (u), down (d), strange (s), charmed (c), and bottom (b) quarks; for the sixth, called the top (t) quark, only theoretical prejudice exists.

The six quarks seem to go in pairs together with the three lepton families.

Each quark flavour has an internal hidden (unobservable) quantum number (called colour), which can take three discrete values; only colourless particles (i.e. containing at least three coloured quarks or a pair of quarks and an antiquark) seem to be observable in nature. A direct consequence of this is that free quarks are not detectable (but this is only a hypothesis!)

Inside the hadrons, the quarks are bound together, and the particles responsible for this (strong) binding force are eight massless, chargeless field quanta called "gluons"; the gluons are coupled to the colour field very much as the photon couples to the charge field.

Nobody knows how many quark species exist in nature.

3. THE FUNDAMENTAL INTERACTIONS

We have seen that one of the aims of high-energy physics is to look for an exhaustive list of "elementary" particles (i.e. indivisible entities out of which all existing particles are made) and to study their static properties (such as their masses and quantum numbers). Another important field is of course to understand their dynamic behaviour, i.e. how these particles interact with each other. Two centuries of brainstorming have succeeded in distinguishing four fundamental interactions between particles (my bet is that twenty more years will be enough to reduce them further into only one).

- The first type of interaction, the gravitation, is only remotely related to particle physics: it is propagated through field quanta called gravitons and coupled to the mass of the objects. Thus only very massive objects are sensitive to this field, and gravitational interactions between particles are so weak that they are completely out of the reach of any experimental technique.

- The electromagnetic interaction is also well known because its propagator, the photon, is a familiar object in our daily life. The photon couples to the electric charge (hence it acts only on charged particles). The electromagnetic interaction is governed by a simple underlying symmetry called U(1), represented by $1 \times 1$ matrices, which transforms a single object into itself (e.g. the emission of a photon transforms an electron into itself).
The strong interaction is responsible for the binding forces of nucleons inside an atomic nucleus or of the quarks inside a nucleon. The field quanta binding the quarks together are eight gluons, which couple to the "colour" field of the quarks (and unlike the photon, since they are also coloured, gluons can couple to themselves). Here the underlying symmetry is called SU(3), and is represented by $3 \times 3$ matrices which can transform any of the three colours of a given quark into any other. The binding energy of the quarks seems to have the unconventional property of becoming very large, when the quarks are pulled apart (property called "infrared slavery"), and null when they get close enough (called "asymptotic freedom").

The weak interaction reveals itself in many "slow" decay processes such as the nuclear beta-decay, but also in interactions between leptons and/or quarks. It is propagated by the so-called three intermediate vector bosons (the $W^+$, $W^-$, and $Z^0$) whose discovery is the main motivation in building the CERN antiproton-proton collider ring. The intermediate bosons are expected, unlike the other massless field quanta, to be very massive (about 100 GeV masses). They couple to the so-called "weak charge", which itself is related to the fact that a particle has its spin (internal angular momentum) oriented in the direction of its motion or not (e.g. an electron can lose its weak charge simply by changing the direction of its motion). The symmetry related to the weak interactions is called SU(2). Here the $2 \times 2$ unitary matrices are used to transform any weak doublet into any other one (provided they have the appropriate weak charges.)

In Table 1 we present some very general properties of the fundamental interactions. It must be said that the strength of an interaction depends on the energy, hence on the distance between interacting particles. The values given in Table 1 are those corresponding to today's physics, namely about $10^{-15}$ cm or 100 GeV. They should converge to a common value (the unification point) at much larger energies.

<table>
<thead>
<tr>
<th>Strong</th>
<th>Electromagnetic</th>
<th>Weak</th>
<th>Gravitational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadrons (Quarks)</td>
<td>All charged particles</td>
<td>Quark Leptons</td>
<td>All massive particles</td>
</tr>
<tr>
<td>Field</td>
<td>Colour</td>
<td>Electric charge</td>
<td>Weak charge</td>
</tr>
<tr>
<td>Field quanta</td>
<td>8 gluons</td>
<td>1 photon</td>
<td>3 intermediate bosons</td>
</tr>
<tr>
<td>Strength</td>
<td>1</td>
<td>1/137</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Range</td>
<td>***</td>
<td>Infinite</td>
<td>Small</td>
</tr>
</tbody>
</table>

*** Correctly commenting on the range of the strong interactions would need more room than is available here.
At this point, a summary of the particle physicists' vision of the Universe would probably be useful:

- All matter is built out of quarks and leptons interacting between themselves, mainly through three fundamental forces (leaving gravitation aside).

- The total number of quarks and leptons is unknown, but the existing ones seem to obey simple symmetry principles. In particular, they are believed to form successive generations (three up to now) of groups, with similar properties from one generation to the other.

- The number of distinct particles in each generation is fixed and goes as follows: 2 quark flavours, each with 3 colours (makes 6), plus a charged lepton and its neutrino (makes 8), plus all their antiparticles (makes 16). One has to double the number to account for the orientations of the spin (this makes distinct particles since they have different weak charges), which makes 32. Then one has to subtract 2 because the neutrino (and the antineutrino) can have only one helicity. Thus we have a total of 30 elementary particles per generation.

- If we want to include the field quanta in the catalogue of particles (but it is not known if they are elementary or not) we have to add to the above number one photon, one graviton, three vector bosons, and eight coloured gluons.

- Many arguments (and three Nobel prizes) tend to prove that at least two of the four interactions (the weak and the electromagnetic) actually unite into a single one (called "electroweak"). The symmetry underlying this unified interaction is a product of the two previous symmetries: $SU(2) \times U(1)$.

4. WILL THERE BE AN END TO HIGH-ENERGY PHYSICS?

The secret dream of any HEPHY is probably to live to see the day when he will be out of his job, i.e. to a time when we will be able to describe the Universe with a minimum number of particles interacting through a minimum number (preferably one) of fundamental forces. Although there is no reason to expect Nature to be as simple-minded as we would wish, we cannot help feeling unhappy with more than a hundred elementary particles and at least three types of interactions. This is why in recent years theoreticians have devoted a large amount of effort to finding possible further unification schemes. Some preliminary results would tend to show that we are progressing in the right direction, and it is interesting to mention a few of these. First, it has been shown that the three types of interactions related to particle physics can well be described by the same type of theories, called 'gauge theories'. It was also found that at very high energies (or very short distances) the three fundamental forces could have the same behaviour. Indeed, this so-called 'Grand Unification' would happen at such large energies ($10^{15}$ GeV corresponding to distances of about $10^{-29}$ cm) that it is impossible to imagine a man-made experiment for exploring such scales. But this unification scheme [based on a minimum symmetry group called SU(5)] has some predictive power which can be tested experimentally. In particular, it predicts that matter is not eternally stable, and that all hadrons (including us) will finally decay into leptons and photons. A large number of experiments are being made just now to try to detect the decay of the proton, but given the expected lifetime (possibly larger than $10^{36}$ years) such experiments are very heavy and delicate. If the Grand Unification scheme proves to be right, we would have the three interactions united into one, and the leptons and quarks would
be grouped into a single family for each generation. However, we would need 12 more very heavy (≈ 10^{16} \text{ GeV}) intermediate particles which would mediate the transitions between quarks and leptons.

One of the outstanding features of this theory is that the range between 10^{-16} and 10^{-29} \text{ cm} (or 10^2 and 10^{15} \text{ GeV}) is a desert as far as particle physics is concerned: nothing new is expected to happen between these two scales. The only new phenomenon expected would be beyond the Grand Unification point, i.e. at energies of about 10^{19} \text{ GeV} where the three particle interactions could possibly unite with gravitation. Thus if all these theoretical predictions are true, there will be no need to try to go to higher energies than those of the already planned or built accelerators. But history is full of examples where people thought they had reached the end of physics, and a few years later had to admit how wrong they were.

5. **HOW IS A HIGH-ENERGY EXPERIMENT DONE?**

Although it is impossible to give an exhaustive list of high-energy experimental techniques in such a short note, we can try to say a few words about the most current ones.

As we said before, a common aim in most high-energy experiments is to create particles and study their properties or their interactions. Thus a high-energy experiment can be characterized by: an incident beam of particles; a target where the interactions occur; and apparatus to study the final states where there are the particles created in the interaction or their decay products.

The particle beams can be found in nature (cosmic rays) but are more conveniently provided by accelerators. There are two types of experimental techniques as far as the accelerators are concerned. One way is to make two particle beams collide inside the accelerator tube with the detectors built around and close to this tube. The colliding beams have the advantage of providing the highest available energies (since the collision takes place in the centre-of-mass of the two particles), but have the drawback of yielding much lower event rates. The second way is to send an extracted beam on a fixed target. The bubble chamber techniques we are interested in can only be used in this case. The CERN Super Proton Synchrotron (SPS), and its American equivalent at Fermilab, have today the highest performance of any accelerator of this kind.

There are two kinds of targets where the beam interacts. The target can simply be passive or blind (e.g. a metal plate), and in this case the information on the interaction point is lost: only the final-state particles leaving the target can be detected. Or the target can be active and provide direct information about what happened at the interaction point. The most current active target is the bubble chamber, a container filled with an appropriate liquid which, under certain thermodynamic conditions, boils (hence provides bubbles) along the track of a charged particle, making this track visible (it can be recorded, for example, on a photographic film).

The analysis of the final-state particles can be done to some extent in the bubble chamber itself. But at higher energies, larger and more complicated electronic detectors are needed in order to have as much information as possible about all the final-state particles (including neutrals).
Most of the highest-energy experiments use purely electronic detectors (together with blind targets). The combination of an active target (such as the bubble chamber, but also nuclear emulsions, solid-state detectors, streamer chambers, etc.) and electronic counters is called a hybrid spectrometer, and EHS (the European Hybrid Spectrometer) is one of the very few permanent ones existing in the world.

A word should be said about one of the most interesting aspects of a high-energy experiment, namely its pluridisciplinarity. Building and running a spectrometer such as EHS needs contributions from experts in many fields, such as thermodynamics, mechanical engineering, optics, electronics, chemistry, radiation safety, computer science, and so on.

6. WHY HIGH-RESOLUTION TECHNIQUES?

In the late 40's a new family of particles was discovered which, because their behaviour was not well understood, were called "strange". The major contribution to the discovery and to the study of the strange particles came from the so-called track chambers, of which the above-mentioned bubble chamber is the most glorious example. The reason for this is simple: most of the ground-state strange particles undergo a weak decay after a mean lifetime of the order of $10^{-10}$ s. Assuming that they move with a speed close to that of light, this means that the average distance between their production and their decay is a few centimetres. Thus the ideal instrument for detecting them is something where one can visualize, at the same time, their production and their decay. One may wonder why it is so important to see their decay. The answer also is simple: when an interaction takes place between say, two protons, there are a lot of particles produced, mostly pions. If we look at the particles coming out of a blind target, we see essentially pions and nucleons. Unfortunately the strange particles also decay into pions and nucleons. Thus, downstream of a blind target, there is no means of finding out if a strange particle was produced except by an indirect method which consists in computing the associated mass of combinations of final-state particles (two-by-two, three-by-three, etc.) and seeing if there is a combination corresponding to the expected mass. It is obvious that if the decay can be seen, this allows the immediate selection of the right combination and an easy identification of the particles: the visible decay of a strange particle can be considered as a "signature" of their production, and the signature is one of the most important features of experimental particle physics.

Hence the bubble chamber was a very efficient instrument for the study of strange particles. But let us first see what must be the characteristics of a bubble chamber well adapted to such a task. The particle tracks are visible in a bubble chamber because the charged particles which cross the chamber ionize the liquid, and if the liquid is then expanded, the region around the ionization starts boiling before the rest, producing visible bubbles. A bubble chamber is characterized by its volume, the bubble size, the bubble density, and many other parameters. The chambers used for the study of strange particles (but not only for that, of course) currently have sizes going from 2 m to 4 m length. They have to be that large for several reasons. The first is that the few centimetres of range before decay correspond to the lifetime of the strange particles at rest. When we take into account the Lorentz factor, at high energies the decay distances can go up to several tens of centimetres. Another reason is that we not only need to observe their decay but also to measure their energy and momentum, and for that the bubble chamber is usually installed inside a magnetic field and, provided the tracks are long enough, measures their radius of curvature.
from which the momentum is easily computed. As for the bubbles, in these big chambers the
density is currently around 10 bubbles per centimetre and the bubble diameter is between
100 and 500 μm.

All strange particles contain the s quark which is, with the u and d, one of the "light"
quarks (with a presumed mass smaller than that of the proton). In 1974 there was the dis-
covery of the first particle containing strange quarks (called the J/ψ), the lightest of the
heavy quarks. One of the main motivations (but not the only one) of the high-resolution
techniques is the study of the "charmed" particles, i.e. containing the c quark. The reason
why we talked at some length about the strange particles and how to detect them, is that now,
20 years later, the story of the charmed particles is nearly the same. Indeed it was dis-
covered that the weak decays of charmed particles occur with lifetimes of the order of
$10^{-13}$-$10^{-12}$ s. At the same time, much as in the case of the strange particles, the decay
products are anonymous (all of them can be produced in processes much more frequent than
charm production) and, what makes things worse, the probability to produce a charmed particle
in a high-energy collision is at least 100 times smaller than for strange particles. All
this leads to the conclusion that, to extract a charm signal from the background of current
hadron production, we need a very efficient signature. Such signatures were looked for
(and some of them, such as the "prompt leptons", are extensively used in pure counter experi-
ments) but it must be admitted that, after eight years of a major experimental program, our
knowledge about charm is something between "poor" and "not so bad".

This is why the techniques that were used for the detection of the strange particles
were likely to inspire a similar method for charm. Particles with $10^{-13}$ s of rest lifetime
produced at, say, a few hundred GeV of incident energy, decay on the average after a few
hundred microns: to be able to see such decay lengths (which is, by the way, probably the
best signature for charm), we obviously need something better than bubbles of 300 μm. Our
needs in resolution will be explained during this colloquium, but we can already outline a
few orders of magnitude. To be able to detect charmed particles efficiently via their weak
decays, we found out that 50 μm of resolution (bubble size) and 100 bubbles per centimetre
were the minimum, the optimum conditions being a resolution of 5 μm and a few hundred bubbles
per centimetre. It is easy to see that small bubble chambers are better adapted to the optics
necessary to obtain such resolutions, and such small devices have to be completed by a down-
stream spectrometer to analyse the final-state particles (hence the need for hybrid spectro-
meters). The need for holography will also be explained in detail during the colloquium, but
we already know that not only will it be very useful for a whole family of interesting experi-
ments but also that such experiments are feasible (a first holographic bubble chamber test in
a beam was performed at CERN in June 1980, and a physics experiment first took data in
October 1981).

Let us conclude with two remarks. The first is that in this introductory report we put
the emphasis on the role of the bubble chambers, but it would be unfair to ignore other tech-
niques which, as far as high resolution is concerned, present very promising features, some
of them even lessening the drawbacks and weaknesses of bubble chambers (such as their slowness
or limited resolution). I am convinced that we will hear more in the future from nuclear
emulsions, streamer chambers, solid-state detectors, etc.
The second remark concerns the physics prospects of high-resolution techniques: today charm physics is the main motivation for such techniques, but we already know that they could be made use of in other fields, such as the study of the fifth quark (b) and related particles, which is just at its beginning, and that of the recently discovered heavy lepton (called the tau). Many other ideas about the use of high-resolution techniques, and specially of holography, are circulating just now, and it is very likely that as soon as the first-generation experiments will prove their feasibility (in particular for the hologram analysis), many others will follow. The time seems appropriate for setting up a close collaboration between high-energy and photonics physicists, to be ready for the near future when things will really start moving.
MOTIVATIONS OF THE WORKSHOP

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The fundamental motivation of this Workshop lies in the desire to determine, with some precision, the properties of elementary particles whose mean proper lifetimes are less than or of the order of $10^{-12}$ s, and whose typical production cross-sections are small (i.e. a few microbarns or less) -- particles such as, for example, charm particles, beauty particles, and the $\tau$-lepton.

With the creation of LEBC in 1978 and experiment NA13, we have proved that high-resolution hydrogen bubble chambers can be used to detect such short-lived particles. The subsequent EHS/LEBC experiment, NA16, is currently proving that a high-resolution hydrogen bubble chamber equipped with a powerful multiparticle spectrometer, and used by a dedicated and motivated team of researchers, at present constitutes the most successful technique for short-lifetime particle research.

Even so, we have not yet taken full advantage of the technique, and therein lies the principal motivation of this Workshop.

Experiment NA16 has pinpointed the major limitation arising from the use of classical optics: the available depth of field is proportional to the resolution squared. Thus better resolution yields a smaller useful bubble chamber volume and increases the difficulty of performing high-sensitivity experiments. For all practical purposes, holographic photography decouples resolution from depth of field of view and therefore holography appears to be the solution to the dilemma.

In this atmosphere, experiments NA25 and NA26 were conceived and bubble chambers HOBC and HOLEBC were born. In fact, NA25 and NA26 have produced beautiful holograms of events (in heavy-liquid and hydrogen bubble chambers, respectively). Bubbles down to $\sim 10$ $\mu$m diameter have been resolved, and successful holograms have been produced with the full depth of the bubble chamber ($\sim$ few centimetres) crammed full with several hundred particle tracks.

Nevertheless, we are far from the situation in which we can expect to produce reliably hundreds of thousands of holograms -- each containing an event of interest! We do not yet know how efficiently we can scan large quantities of holograms or how we will extract the interesting physics.

In addition to these practical motivations, we also have somewhat more esoteric considerations. We are at present about one order of magnitude away from feasible theoretical resolution limits. Can we expect optimization to yield resolution as good as that with the nuclear emulsion technique ($\leq 1$ $\mu$m)? If we can, will our bubble chambers then provide us with enough bubbles per centimetre to define tracks? Another limitation to our technique comes from the bubble chamber duty cycle (and the accelerator duty cycle too, but we cannot do much about that). Present fast-cycling bubble chambers are sensitive only a few per cent of the time. Would a continuously sensitive bubble chamber help, in practice? or are the operational constraints so severe as to make such a device worse than present devices?

These and other considerations, then, aimed mainly at practical progress and optimization of existing techniques, and at increasing reliability and efficiency, should be the major motivation of this mixed gathering of experts.
A subsidiary motivation involves determining the most efficient usage of the European Hybrid Spectrometer (EHS) and its infra-structure for this type of physics. In particular, RCBC is the rapid-cycling hydrogen bubble chamber designed especially for EHS. It occupies a privileged position inside the vertex magnet M1, and the rest of the EHS gadgets are well matched to it. It has thus occurred to many to consider the use of RCBC rather than the small specially built lexan bubble chambers (LEBC et seq.). However, is RCBC, in fact, suited to this type of physics? Can sufficiently high resolution be attained over a sufficiently large volume of liquid hydrogen? Should RCBC be replaced by a large streamer chamber which would give invaluable track and ionization information? Can RCBC compete with such a combination of streamer chamber inside the magnet M1 coupled with a small fast-cycling upstream vertex detector? Some progress should be made in the consideration of these and related questions.

Finally, the trickiest problem of all will not be covered in much depth during this Workshop. This is the problem of finding suitable and efficient means of on-line selection of interesting events -- what we euphemistically refer to as the trigger problem. Since not much formal time is devoted to this crucial item, we expect this subject to motivate many of our coffee-break discussions. (Post scriptum: it did).
DEPENDENCE OF TRANSVERSE AND LONGITUDINAL RESOLUTION
ON SOME PARAMETERS DEFINING THE SET-UP IN HOLOGRAPHY

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1. INTRODUCTION

With the aid of holographic techniques a good spatial resolution can be obtained over a large depth of field. This arises from the fact that these two quantities are decoupled in holography, which is not the case in standard photography. We have investigated the sensitivity of spatial holographic resolution to different parameters which characterize the optical set-up. Important parameters are:

\( \ell \) : the distance between the object and the holographic plate,

\( \theta \) : the angle between the reference beam and the object beam,

\( I_r/I_o \) : the ratio of the intensity of the reference beam to that of the object beam.

In this work a quantitative study has been made of the transverse resolution \( R_{xy} \) and of the longitudinal resolution \( R_z \) as a function of these parameters. Special attention was paid to the dependence of the spatial resolutions on the distance parameter \( \ell \) in the different set-ups. It is known that the transverse resolution \( R_{xy} \) varies linearly with \( \ell \) from the classical relation:

\[
R_{xy} = 1.22 \frac{\lambda \ell}{D},
\]

(1)

where \( \lambda \) symbolizes the optical wavelength and \( D \) the effective diameter of the reference beam. Furthermore, one can show that the longitudinal resolution \( R_z \) is related to \( \ell \) by

\[
R_z = \frac{8\lambda \ell^2}{D^2}
\]

(2)

by calculating the intensity pattern resulting from the holographic image of two points situated along an axis perpendicular to the holographic plate. The application of this relation to bubble-chamber recordings remains, however, to be verified.

2. EXPERIMENTAL SET-UPS

All tests presented here were performed in the Applied Optics Institute (VUB-Brussels). The holograms were recorded on Agfa 8ES6 plates, using an Ar-ion laser (supplied by Spectra-Physics) having a maximum power of \( \sim 1 \) W. This laser was operated at a wavelength of \( \lambda = 5145 \) Å throughout all tests.

In order to define the spatial resolutions in an unambiguous manner a USAF test target was used to serve as the object. This target consists of a glass plate on which chromium elements are evaporated. The size of these elements ranges from 500 to 1 μm. Figure 1a

*) Navigator I.I.K. W.
summarizes the most important characteristics of this target. In Fig. 1b a detail of the target is shown containing the smallest elements. This photograph was made from the screen of a TV monitor, connected with a vidicon-camera equipped with a microscope viewing the test target.

Basically two set-ups were tested in this work:

a) The "in-line" set-up, where the reference beam is parallel to the object beam. The test target was put perpendicularly to the incoming beam, and different values of \( \ell \) were chosen. During these tests information was obtained on \( R_{xy} \) and \( R_z \).

b) The "two-beam" set-up, where an angle \( \theta_{ro} \) was imposed between the reference beam and the object beam. Tests were done at \( \theta_{ro} \approx 30^\circ \) and again different \( \ell \)-values were taken. Furthermore, two different intensity ratios were tried between the two beams. With this set-up it was only possible to obtain information on \( R_{xy} \).

3. **IN-LINE TESTS**

Figure 2 displays the set-up used to study in-line holography. At the recording stage the test target was placed at different distances \( \ell \) from the holographic plate. At the replay stage the hologram was mounted on a device which could be moved along the three axes x, y, and z. This device was equipped with a micrometer on each axis. The real image of the hologram was viewed through a system consisting of a microscope equipped with a vidicon camera, connected with a TV monitor. Eight holograms were taken at different \( \ell \) values.

3.1 Transverse resolution \( (R_{xy}) \)

The best transverse resolution \( (r) \) of a hologram was defined as the size of the smallest elements which could still be distinguished in the real image (Fig. 3). The error (\( \Delta r \)) was defined by comparing the size of these elements \( (i) \) with that of the previous elements \( (i - 1) \) and that of the next elements \( (i + 1) \) on the target. Figure 4 shows the values of \( R_{xy} \) as a function of \( \ell \), obtained during this test. A straight line was fitted through these points, represented by the following equation *)

\[
R_{xy} = a + b\ell .
\]  

(3)

The value obtained for the slope factor \( b \) was then used to derive the effective beam diameter \( D \) appearing in Eq. (1):

\[
D = 3.4 \pm 0.4 \, \text{cm} .
\]

3.2 Longitudinal resolution \( (R_z) \)

In order to compute the longitudinal resolution of a holographic image a statistical method was applied. Again the real image of the hologram was viewed through the chain consisting of a microscope, a vidicon camera, and a TV monitor **).

*) The constant \( a \) was introduced to take into account the intrinsic resolution of the measurements.

**) The microscope was equipped with an objective having magnification \( \times 20 \); no ocular was used and the vidicon camera was operated without an objective.
The holographic plate was mounted on the device, which was movable along the three axes \( x, y, z \), and which was equipped with a micrometer on each axis. Figure 5 illustrates the procedure of the measurements:

i) A given element of the target image was focused as accurately as possible (in this way the \( z \)-coordinate of the element was adjusted).

ii) Then the element was moved in the plane perpendicular to the microscope axis until it coincided with a cross marked on the TV screen (in this way the \( x \)- and \( y \)-coordinates were adjusted).

iii) Next the position of the element was recorded from the read-out on the three micrometers. In each hologram thirty measurements were performed on different elements.

Next the measured coordinates of the elements were processed as follows. A plane was fitted through the 30 points, expressed by

\[
  z = \alpha x + \beta y - \gamma. \tag{4}
\]

This was done in practice by minimizing the sum of the squares of the distances of these points to a given plane defined by the parameters \( (\alpha, \beta, \gamma) \):

\[
  F(\alpha, \beta, \gamma) = \sum_{i=1}^{n} D^2(x_i, y_i, z_i) = \min \tag{5}
\]

\[
  D(x_i, y_i, z_i) = \frac{\gamma - (\alpha x_i + \beta y_i - z_i)}{\sqrt{1 + \alpha^2 + \beta^2}}. \tag{6}
\]

After having fixed the parameters \( (\alpha, \beta, \gamma) \) at their best value, Eq. (6) was used to compute the distances of the measured points to this "best" plane. These distances were found to be centred around zero with a given spread expressed by the corresponding r.m.s.\(^{\text{hol}}\). This r.m.s. is caused by the deviation of the measured points from the best plane in the \( z \)-direction. Hence, it can only be a reflection of the longitudinal resolution \( (R_z) \) of the hologram and of the inherent measurement precision. In order to take this measurement precision into account the same procedure was repeated on the actual elements of the original test target. In this way the following intrinsic resolution was obtained:

\[
  \text{r.m.s. target} = 17 \pm 3 \text{ \( \mu \)m}. \tag{7}
\]

The longitudinal resolution for a given hologram was then defined as:

\[
  R_z = \sqrt{\text{r.m.s.}^2_{\text{hol}} - \text{r.m.s.}^2_{\text{target}}}. \tag{8}
\]

The error on \( R_z \) was computed using a Monte Carlo method.

The results of this test are shown in Fig. 6. From these data points one cannot conclude whether \( R_z \) really exhibits a parabolic variation as a function of \( k \) as was suggested by Eq. (2), although the latter predicts the right order of magnitude of \( R_z \) within the range
of $z$-values under investigation. However, if one fits a parabola through these points, expressed by

$$ R_z = a z^2, $$ (7)

one can derive again a value of the effective beam diameter D from Eq. (2):

$$ D = 4.3 \pm 0.1 \text{ cm}. $$

This value is not in disagreement with that derived from the transverse resolutions.

4. TWO-BEAM HOLOGRAPHY

Figure 7 illustrates the set-up used to study spatial resolution in "two-beam" holography. At the recording stage the object beam was focused through the target onto a small spot of the holographic plate, to eliminate the zero-order component of the object beam. This was done by means of a converging lens ($L_4$). The reference beam was oriented at an angle of $30^\circ$ with respect to the object beam. At the replay stage the object beam was blocked and the holographic plate was mounted in a similar way to that described in Section 3.

A rough measurement was made of the average intensities of the object beam and the reference beam. A test was done where both intensities were about equal and another one where the reference beam was about 15 to 20 times as intense as the object beam. Figure 8 summarizes the results for the transverse resolutions found for these two tests. One notices that these results vary between 15 and 35 $\mu$m for $z$ inferior to 20 cm. Moreover a pronounced astigmatism of the image was observed, which ranged typically between 50 and 500 $\mu$m. The presence of "ghost" images in some places of the hologram also increased the difficulty of analysing the holograms. A general conclusion about this specific set-up was that all results were definitely worse that those of the "in-line" set-up described in Section 3. Hence, if one really needs off-axis holography to perform high-resolution experiments, a different set-up should be used.

5. CONCLUSIONS

Quantitative measurements were made of spatial resolutions in "in-line" holography and in "off-axis" holography. With "in-line" holography transverse resolutions were measured between 2 and 10 $\mu$m for distances of $z$ between the object and the holographic plate ranging from $\sim$ 4 to 40 cm.

In the same set-up longitudinal resolutions were measured between 20 and 300 $\mu$m. Above $z = 35$ cm it was very difficult to perform good measurements of this quantity. This was due to the fact that at such distances one is practically unable to determine a best focus of the image. From the data presented here one can conclude that high-resolution experiments should be done for optical distances reduced as much as possible. Furthermore, the large values of $R_z$ (compared to $R_{xy}$) should be kept in mind if one wants to perform very accurate measurements of coordinates. Indeed, at very short distances ($z \sim 4$ cm), the minimal r.m.s. of such measurements appeared to be $\sim 20$ $\mu$m.

When using a set-up for off-axis holography worse results were obtained and a significant astigmatism of several hundred $\mu$m was observed throughout the images. It was impossible to
measure transverse resolutions below 15 μm for distances of ≤ inferior to 20 cm. Owing to the poor quality of the real image in this set-up (astigmatism, ghost images, etc.), it turned out to be impossible to measure the corresponding longitudinal resolution. One concludes here that the specific off-axis set-up used in this test is most probably not applicable in high-resolution experiments. If off-axis holography were really required in an experimental set-up, more investigations should be carried out in this field in order to obtain a deeper insight into all problems met so far.
Fig. 2

M.O.: Microscope objective
S.F.: Spatial filter
C.L.: Converging lens
H.: Holographic plate

Fig. 3
Fig. 8
TRANSPARENT MEDIA CHARACTERIZATION USING SUB-PICO SECOND DYE LASER

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ABSTRACT
A new passively mode locked laser source developed at the Center for Laser Studies yielded pulses shorter than 0.14 ps, at a rate of 250 MHz or 0.3 ps pulses at a rate of 500 MHz. The laser and its modes of operation are described. With this source and a second order cross correlation technique similar to the autocorrelation used to determine the pulse duration, time domain reflectometry measurements can be made with a resolution of 40 μm. Three dimensional images can be made by time resolving the backscattered radiation of a beam scanned through a medium. The depth resolution of 0.1 μm can be carried over to the other two dimensions by computer reconstruction. The new technique should have important applications in medicine and biology. Because of the short duration of the laser pulses, high peak intensities can be used without damage to the tissues. Therefore, light measurements can be conducted through a larger depth than with continuous radiation.

1. INTRODUCTION

New possibilities in Optical Metrology are emerging from the recent development of a picosecond laser source at the Center for Laser Studies. The two unique characteristics of our source, that are instrumental in the applications described below are:

- a pulse duration in the range of 0.1-0.2 ps, giving us the capability of making time domain reflectometry measurements with a resolving power of ≈ 50 μ;
- a repetition rate as high as 500 MHz, which should make the recording of three dimensional images possible in fractions of seconds.

We present an experimental set up to time resolve the light backscattered as the continuous train of pulses is sent through various media. This technique of optical Time Domain Reflectometry (TDR) will enable us to localize small defects in optical fiber connectors and to determine the light intensity distribution inside scattering and absorbing media. Angular scanning of this one dimensional information can provide three dimensional images of biological objects. For instance, eyes, breasts and arteries located near the surface are regions of the body amenable to optical imaging. Through the use of computer reconstruction techniques, it should be possible to convey the unique depth resolution to three dimensions. Before discussing these applications (sections 3-5), we will give a brief description of the operation of the source, its limitations and possible improvements.

2. THE SUB-PICOSECOND LASER

2.1. Description
The source of ultrashort pulses is a passively mode locked dye laser, pumped by a continuous Argon Laser. This laser differs from conventional passively mode locked system\(^1,2\) by
1. The absence of any dispersion in the cavity around the wavelength of interest.
2. A simpler cavity - the mode locking dyes are mixed in the same solution as the laser dye, eliminating the need for an additional dye jet\(^1\) or cell\(^2\) inside the cavity.
3. A cavity length shorter than (optimally equal to) 60 cm.

The absence of intracavity dispersion is the most stringent requirement, and was met through elimination of all conventional wavelength tuning elements. The operation of the laser is limited to the wavelength range of 500 nm to 620 nm by the reflective properties of the output mirror. The particular shape of the reflection spectrum of that cavity mirror is a critical parameter in the short pulse operation of the laser. It is essential that the cavity losses be constant and minimal over a wavelength range broader than that defined by the pulse bandwidth. But it is also essential that the cavity losses increase sharply at wavelengths below 600 nm, to overcompensate the increasing gain of Rhodamine 6G at these wavelengths. A third order reflector centered at 610 nm ideally combined these properties, giving a constant reflectivity of 99.7 % in the wavelength range of interest.

We have made a systematic study of the influence of dye composition on the mode locking characteristics.\(^3\) The shortest pulse durations are obtained with a solution of \(2 \times 10^{-5} \text{ M/l} \) of Rh 6G, \(2 \times 10^{-5} \text{ M/l} \) dioxadecarbocyanine iodide (DODCI), and \(3.5 \times 10^{-6} \text{ M/l} \) malachite green, in ethylene glycol (analytical grade). Aging of the solution is a serious problem that has yet to be solved.

The cavity length is unusually short compared with that of other mode locked systems leading to pulse rates hitherto unequalled for mode locked dye laser (250 to 600 MHz). Ultrashort pulse operation (\(\leq 0.2 \text{ ps} \)) could only be observed for a cavity length shorter than (or equal to) 60 cm (the shortest pulses corresponding to the 60 cm cavity).

2.2. Modes of Operation

The operation of this laser is critically dependent on the pump power intensity. The average power of the dye laser is rather insensitive to changes in argon laser pump power (above threshold). However, the average power in the second harmonic (of the dye laser beam) changes by many orders of magnitude as the pump power is increased over a range of only 0.2W. Two maxima, each only a few mW wide, are observed in the variation of the second harmonic average power as a function of argon laser power. Pulses shorter than 0.2 ps at 4ns interval are measured for a pump power corresponding to the first maximum, and pulses of 0.3 ps at 2 ns interval (2 pulses per cavity round trip time) at a pump power corresponding to the second maximum. This latter mode of operation is the most attractive for metrologic applications requiring a fast data rate, because the pulses are emitted in a continuous train at 500 MHz. The first mode of operation is to be preferred when high resolution is desirable, and is described in more details below.

A second order autocorrelation of the pulse with itself, as shown in Figure 2, gives a measure of the spatial resolution that can be achieved in the optical TDR measurements described in the next sections. The FWHM of the trace reproduced in Figure 1 is 62 \(\mu\)m corresponding to a time delay of 0.21 ps or a pulse duration of 0.14 ps. It should be noted that the autocorrelation of Figure 1 represents an average of a distribution of pulses of different duration and even shorter pulses are present in the train.\(^4\) The envelope of the pulse train is seen to have a modulation at 50 kc. Boxcar integration measurements of the
pulse spectrum and second order autocorrelation shows that the center frequency of the pulses oscillates between 605 and 610 nm, while their duration changes by two orders of magnitude. While the exact nature of this relaxation oscillation is not understood at this point, it is clearly directly related of the generation mechanism of the shortest pulses. It was verified that this relaxation oscillation at 50 kHz was not associated with any noise component from the pump laser. However, the stability of the ultrashort pulse operation was greatly enhanced when this oscillation was externally synchronized through an intensity modulation of the pump power. This was achieved by inserting an electro-optic modulator, driven at 50 kc in the argon laser beam.

![Figure 1](image)

Second order autocorrelation trace of the pulse train.

3. **TIME DOMAIN REFLECTOMETRY (LINEAR INTERFEROMETRIC DETECTION)**

The expression "Time Domain Reflectometry" (TDR) generally refers to a technique for localizing and evaluating defects in electrical cables and connectors, by measuring the time delay between launching a pulse into a cable and the arrival of the reflection from a defect. The same technique can be extended to the optical field. The shortest pulses should enable us to localize a defect in a fiber connector with an accuracy of the order of a micron, or to resolve two defects only 50 μm apart. This is the highest resolution that can be achieved by optical methods through a section of glass of ≈ 10 cm long. Indeed, material dispersion alone is sufficient to "blur" the image of a pair of defects. TDR of that accuracy requires a temporal resolution of the reflected light better than 0.1 ps. This time scale being far beyond electronic capabilities, it is necessary to use purely optical techniques to obtain the required time resolution.

The basic instrument to optically time resolve backscattered beams consists in the assembly of fused silica prisms sketched in Figure 2. The prisms 1 and 2 are optically contacted. The prisms 3 and 4 are coated with chromium spacers, and pressed against prisms 1 and 2 with an adjustable force to provide a controllable beam splitting ratio (by frustrated total internal reflection). Prism 5 is mounted on an accurate translation stage to provide the reference delay. The optical alignment is completed by a) a wedge W rotatable (through a worm gear assembly) around a horizontal axis until the cumulative error of the 90° prisms
(in the plane of the figure) is exactly compensated, and b) a high precision tilt platform mount for prism 5 on the translation stage. A translation speed ranging from 0.2 μm/sec to 2 mm/sec can be selected through a combination of synchronous motors and reduction gears.

Figure 2
Prism assembly for optical time delay reflectometry

Figure 3 shows linear detection of a weak return obtained by the reflection of an antireflection coated glass surface, attenuated 100 x by a neutral density filter (returned intensity ≤ 5.10^-5 of incident beam). With the beam splitting ratio S1 set at 50 %, the beam splitting ratio S2 has been adjusted for equal intensity of the reference and reflected beams impinging on the detector (a photomultiplier RCA IP28). As the optical delay in the reference beam is scanned, an interference pattern is observed for the value of the delay matching time of flight of the reflected original (Figure 3). Such a "linear method" has a few advantages (over the nonlinear methods presented in the following sections) but serious shortcomings:

1. It has a subwavelength accuracy (individual fringes can be identified with a slower scan speed).
2. Being a "non zero method", it requires adjustment of the beam splitter S2 to match the reference and reflected signal beam intensities.
3. The dynamic range is limited to return signal intensities that are at best within a factor 100 (in amplitude) of the most intense return.
4. Since the return beam has to be coherent with the reference beams, this method is limited to the observation of reflections from sharp discontinuities.

Figure 3
Localization of a weak discontinuity by TDR
4. **TIME DOMAIN REFLECTOMETRY (SECOND HARMONIC DETECTION)**

Ideally, the detection scheme should measure the product of reference beam intensity times the reflected signal. Then the backscattered signal is truly "sampled" by the reference signal at a preselected time (corresponding to a predetermined position in the sample to be investigated). Such a product detection can be made easily by measuring the second harmonic generation of type II created by colinear - orthogonally polarized - reference and signal beams, focused in an appropriately oriented frequency doubling crystal. The orthogonal polarization is obtained by inserting a $\lambda/2$ plate in the path of the reference beam (Figure 2). The basic setup is the same as in Figure 2, with a frequency doubling crystal and detection at the second harmonic frequency being substituted to the linear detection. Because of the difficulty of finding good crystals for second harmonic generation of type II at 610 nm, we choose instead a noncolinear arrangement sketched in Figure 4, where a KDP crystal cut for type I second harmonic generation can be used. Instead of being colinear, the reference and signal beams are sent with converging wave vectors into the KDP crystal. The second harmonic generated along the bisector of the small angle made by the intersecting fundamental beams is proportional to the product of the intensity in each beam.

![Prism Assembly for nonlinear TDR.](image)

Either of the set ups described under this heading gives a second harmonic intensity proportional to the product of the intensities in the reference ($I_r(t)$) and backscattered original beam ($I_s(t)$). This product is maximum for the beam splitters reflectivities being respectively $R = 2/3$ for $S_1$ and $R = 1/2$ for $S_2$. To a first approximation, the reference short pulse can be assimilated to a delta-function ($I(t) = a \delta(t-\tau)$), and the detected signal is:

$$ S = a \int I_s(t) \delta(t-\tau) \, dt = a I_s(\tau) $$

While the sensitivity of this technique of optical TDR is proportional to the laser source intensity squared, the signal $S$ is a linear function of the backscattered intensity. Using fast and sensitive detection techniques, this method is potentially capable of detecting very weak backscattered signals. Unlike the interference method, the features to be observed do not need to be localized discontinuities, but can be inhomogeneous distributions of scatterers and absorbers. A large dynamic range should make it possible to apply this technique even to biologic objects. Computer reconstruction has to be used to extract the one dimensional "image" (or 'Opacity function') from the time resolved measurement of the backscattering. Let us
consider a medium with a uniform scattering coefficient $\sigma_s$, and an absorption coefficient $\sigma_a(z)$ to be determined. The opacity function $\sigma_s + \sigma_a = \alpha(z)$ can be calculated directly "on line" from the measurement $S(\tau)$ through the relation:

$$\alpha(z) = \frac{d}{dz} \left\{ \frac{1}{2} \ln S(z) \right\}$$

In order to obtain the highest possible dynamic range with the available pulse duration, the instrumentation described in Figure 5 is being assembled at the Center for Laser Studies (USC). The laser is used in its continuous mode of operation emitting pulses of 0.3 ps at a rate of 500 MHz. A conventional all electrostatic Varian Photomultiplier Tube VM-152D was selected for this application. The conventional tube was preferred to crossed field and microchannel photomultipliers, because of its broad dynamic range. Indeed, in the conventional tube, the gain can be varied by several orders of magnitude during the depth scan. This photomultiplier has an impulse response width of ± 1 ns, thus quite adequate to separate successive pulses in the train. Some signal to noise discrimination is provided by a 600 MHz preamplifier and a resettable integrator following a fast detector. The integrator provides an improvement of the signal to noise of approximately a factor of 10 by reducing the data rate to 10 MHz, a repetition rate readily accessible to A/D converters for further digital data processing. Further (digital) averaging can be made if the signal to noise need to be improved.

![Diagram](image)

**Figure 5**

Instrumentation for optical TDR.

5. **THREE DIMENSIONAL IMAGING**

The time domain reflectometry technique described above associated with a fast scanner, can be used to obtain three dimensional images. In order to have a transverse resolution comparable with the depth resolution, it is necessary to focus the laser light in the plane of observation defined by the reference delay. It is then necessary to change the position of lens and scanner for each field of depth (or each value of the reference delay). The motion of the scanning optics would have to be linked to the motion of the reference delay, which is impractical. Using directly parallel beam configuration eliminates the problem of depth of field adjustment, but the transverse resolution is then limited to approximately 1 mm by diffraction. It is then still possible to carry over the optical TDR resolution of 0.1 mm to three dimension by computer reconstruction of three dimensional pictures taken from various angles of illumination. Figure 6 shows schematically how this reconstruction could occur in a transaxial plane. The beam is scanned successively laterally and angularly by rotating glass plate and an optical scanner. The scanned and displaced beams are imaged
inside the object to be investigated. Reconstruction is made by small areas 1 mm × 1 mm. Beams at different angle sampled every 100 mm, form intersecting grids around P. Using these samples at different angles, an iterative algorithm will be used to reconstruct the small region around P. Provisions have to be made in the algorithm to appropriately account for regions which lie outside the 1 mm reconstruction zone because these regions contribute to the projection data. To reconstruct an approximately 1 mm diameter region on a 10 × 10 grid with a grid size of ~ 100 μm, 8 angles (around 180°) are needed. Generally, the viewing angle will be smaller, however, algorithms have been developed for reconstructing from views which cover a limited angle. A global image will be reconstructed by "sliding" the local grid across the object. This process will have to be iterated, since each local image is affected by its neighbors. It is expected that a few iterations will produce a high resolution global image.

![Diagram](image)

**Figure 6**
Scanning configuration for optical TDR.

It is interesting to compare these three dimensional imaging techniques to computed X-ray tomography. The large attenuation of the optical radiation limits its depths of penetration. On the other hand, a larger absorption cross section offers the advantage of enhanced contrast. The transmission factor is averaged over the full length of body traversed in X-ray tomography. The backscattering from a well defined depth is averaged over the beam cross section in optical TDR. The possibility of proceeding from local reconstruction is unique to the Optical TDR. Because of the low energy in the subpicosecond pulses, radiation damage should not become a factor even after amplification. The transmission factor of tissues to subpicosecond pulses have not yet been measured. Since many absorbing substances will have characteristic times longer than the pulse duration, their transmission characteristics can be expected to be different than for continuous radiation.

5.1. Acknowledgements

The development of the subpicosecond laser source was supported by NSF under grant No. EN7721435. We gratefully acknowledge fruitful discussions with Dr. G. Huth and M. Singh on the topic of computed optical tomography. Mr. H. Sallaba provided invaluable assistance, the experimental work with the subpicosecond source.
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FAST CAMERAS FOR FAST CYCLING BUBBLE CHAMBERS

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1. INTRODUCTION

Cameras for bubble chambers are an important part of the data-taking process because they can limit the data-taking rate, and the track reconstruction precision in space is very much dependent on the film positioning inside the camera.

It is clear that at time of exposure the film must be perfectly flat and stationary. This is commonly done by vacuum suck-down on a flat film back. This perfect positioning must be maintained even for fast cameras and this is one of the difficulties in camera design. It is interesting to note that the requirements of flatness for holographic cameras have been found quite similar to what is currently offered by conventional bubble chamber cameras (see Fig. 1).

Here we will not dwell on camera design but mainly study two special requirements for cameras used in fast cycling bubble chambers coupled to a spectrometer, like LEBC, HOLEBC, HOBBC, and RCBC, mainly the speed requirement and the data-board printing. Some conclusions will be derived for the proposed "Charm 82" experiment (now approved as NA27).

2. SPEED REQUIREMENT

It can be said that there is a need for fast cameras because there are fast cycling chambers and there is no selective trigger available.

If we define

\[ p: \text{probability of having a good event per expansion}, \]
\[ N: \text{number of expansions per burst}, \]
\[ F: \text{frequency of the bubble chamber}, \]
\[ f: \text{frequency of the maximum data-taking rate due to the camera dead-time (camera frequency \( \geq f \)}, \]
\[ k: = \frac{F}{f}, \]
\[ n: \text{number of pictures per burst}, \]
\[ \eta: \text{data taking efficiency} = \frac{n}{pN} \]

then

\[ n = \frac{pN}{1 + p(k-1)} . \]

Figure 2 shows the evolution of the data yield as a function of \( p \) and \( k \).

For the experiment NA16 using LEBC we had \( p = 0.25 \), and \( n \) was around 0.85 for \( k = 2 \), i.e. a 30 Hz chamber coupled to a 15 Hz camera. Now it is clear from Fig. 2 that had a selective trigger existed to reduce \( p \) to around 0.05 then the camera speed would have been unimportant.

Figure 3 shows one RCBC capstan which was used for NA16. For this format (50 mm film and 66 mm frame length) we have reached a camera speed of 24 pictures per second. However this design is not readily adaptable to a longer frame length and we are at present working on a modified system.
3. **FILM LABELLING AND DATA BOARD**

Another important feature of bubble-chamber cameras is the labelling of frames done using a so-called data board. In hybrid experiments the pictures have to be tied to a record on magnetic tape and the correct labelling of both the pictures and the magnetic tape record is of prime importance as late unscrambling is practically impossible\(^1\).

Thus already for RCBC it had been decided that:

i) information printed on films and magnetic tapes, even wrong, must be the same for a particular event;

ii) data boards must have an error detection scheme which also writes on the associated magnetic record what has really been printed on film.

It is interesting to see that for these reasons, if RCBC is equipped with a high-resolution channel, high-resolution pictures without the normal views (OFVT having prevented their taking) will not be numbered to keep the unambiguous correspondence between all the views and the magnetic record for a particular event.

4. **APPLICATION TO THE "CHARM 82" EXPERIMENT, NA27**

For the proposed experiment "Charm 82" using HOLEBC, no selective trigger will be available at the start of the experiment in spring 1982; thus fast cameras must be built up to keep the data-taking rate high enough. HOLEBC will run around 30 Hz and again a 16 Hz camera will be well adapted. Although a longer frame length will be needed here (see later) we are confident that that speed can be reached safely.

To get a data-board system with all the needed qualities or so short a time scale it has been decided to use on these cameras the full RCBC data-board system. This has also the advantage of being fully compatible with the NORD-10 data acquisition computer.

5. **FILM FORMAT**

Taking into account the 1 to 1 magnification ratio for HOLEBC and the requirement for the maximum measuring field for ERASME\(^2\) the frame length has been fixed at 116.5 mm (see Fig. 4).

The same film format will be used for the future RCBC high resolution channels.

* * *

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Fig. 1 General view of the holographic camera used in H0BC for the experiment NA25. The camera is in fact a conventional bubble-chamber camera, as the requirements for holography are very similar to what is needed for conventional stereoscopic cameras.

\[ \eta = \frac{1}{1 + p(k-1)} \]

- \( p \): probability of a good event per expansion
- \( k \): chamber rep. rate
- \( \text{camera rep. rate} \)

Fig. 2 Data yield as a function of the trigger efficiency (\( p \)) and the camera speed (\( k \))
Fig. 3 RCBC capstan used also for LEBE during NA16. With this frame length (66 mm) a speed of 24 pictures per second has been reached.

Fig. 4 Envisaged film format for HOLEBC and the high-resolution channel for RCBC
HOBC, A HEAVY-LIQUID HOLOGRAPHIC BUBBLE CHAMBER: FIRST RESULTS

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1. INTRODUCTION

HOBC, an acronym for HOlographic Bubble Chamber, is a small (2 L) heavy-liquid rapid-cycling bubble chamber which has been designed specifically for the use of in-line holography for the experiment NA25 \textsuperscript{1,2}).

2. DESCRIPTION OF THE CHAMBER

This is a see-through chamber with two good-quality optics windows in BK7 (Fig. 1). The main heat exchanger is at the top, the expansion system at the bottom. The chamber is sealed by a 200 mm diameter stainless-steel bellows (Fig. 2). One of these has already been cycled for more than 15 million cycles. The chamber is closed by a piston, inside which a heat exchanger is fitted for water to circulate (Fig. 3).

After testing during June/July 1981 in the CERN Proton Synchrotron (PS) test beam, in October of that year the chamber was moved into the H2 beam at the CERN Super Proton Synchrotron (SPS) for the experiment NA25 (Fig. 4).

3. OPERATING CONDITIONS

The operating conditions used during NA25 are as follows:

- **Filling:** C\textsubscript{2}F\textsubscript{6}Cl
- **Operating temperature** 48 °C
- **Static pressure** 26 bar
- **Vapour pressure** 6 bar
- **Expanded pressure**
- **Liquid density** 1.25
- **Piston stroke** 1.25 mm
- **Expansion cycle duration** 5 ms
- **Bubble density** 200 to 220 cm\textsuperscript{-1}
- **Laser delay** 3 μs

A total of 12,000 high-resolution holograms with 10 μm bubbles were produced\textsuperscript{2,3})

3.1 Temperature

The choice of the operating temperature was made with a view to obtaining the maximum bubble density.

Figure 5 (the thermodynamic diagram for freon-F115) shows the minimum expanded pressure reachable 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.

This can be explained by saying that below 48 °C the minimum expanded pressure is limited by the growth of parasitic boiling (these parasitic bubbles grow more quickly with decreasing temperature, as do the track bubbles). Above 48 °C the expansion is fast enough to
overcome the parasitic boiling, and the foam limit is reached on the hotter point of the chamber.

With a faster expansion or a cleaner chamber the optimal temperature for maximum bubble density would be displaced towards the cooler temperatures. However, above 48 °C the bubble density variation with temperature is a slowly decreasing function, and later we will try to run at a higher temperature (around 58 °C) to slow down the bubble growth.

3.2 Cycling rate

At the beginning of the tests we had problems in making high-resolution holograms, even without expanding, because of movement of the liquid due to natural convection, until we found that by slightly stratifying the chamber we had a perfect optical background. Afterwards we always operated the chamber in this uncommon condition, keeping the bottom of the chamber 0.3 to 0.4 degree cooler than the top. In this situation we obtained very good results up to 10 Hz cycling rate at low beam flux (600 particles per second).

However, we came up against another problem when we tried, at the SPS, to mix high beam fluxes (up to $2 \times 10^6$ particles per second) and a repetition rate of 10 Hz. We saw that although the bubbles are rapidly recompressed (around 20 ms), the heat generated by this re-compression diffuses slowly in the bulk liquid.

It is interesting to see how tracks (or track remnants) look between expansions, by using laser delays up to 400 ms. Figures 6 to 14 are direct prints of in-line holograms. Once the bubbles have disappeared, what is seen is the 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 700 ms between expansions to ensure the quality of the holograms taken, because their "scannability" was considered the most important point.

4. REMARKS ON HEAT DIFFUSION IN LIQUIDS

To understand what has been seen, it is interesting to compare freon-F115 with liquid hydrogen, in which holograms were also recently produced\(^1\). Although the quality of these holograms was still not high, it was sufficient to judge that the effect of heat dissipation in liquid hydrogen is less severe, as HOLEBC could be expanded at 30 Hz.

Clearly one of the most important parameters is the variation of optical index with temperature, $dn/dt$. Figure 15 shows this variation for freon-F115, and Fig. 16 for liquid hydrogen; there is a factor of 3 in favour of F115. In other words, to have the same difference in optical paths, a thermal gradient 3 times higher is needed in freon-F115.

Now, as there seems to be a problem of heat diffusion, it is interesting (as a simple model) to compare the exchange by natural convection around a wire when using freon-F115 or liquid hydrogen.
There is a correlation between the product of the Grashof (Gr) and Prandtl (Pr) numbers and the Nusselt (Nu) number,

$$Nu = 0.53 (Gr \cdot Pr)^{1/4} \quad [McAdams^{5}]$$

with

$$Gr \cdot Pr = \frac{c_p \rho^2 g \beta \Delta T D_0^3}{\mu k}$$

$$Nu = \frac{h_c D}{k}$$

where

- $c_p$: specific heat of liquid $J/(kg \cdot K)$
- $\rho$: specific mass of liquid $kg/m^3$
- $g$: 9.81 $m/s^2$
- $\beta$: coefficient of volumetric expansion $1/K$
- $\Delta T$: temperature difference between wire and bulk liquid $K$
- $D_0$: wire diameter $m$
- $\mu$: viscosity of liquid $kg/(m \cdot s)$
- $k$: thermal conductivity of liquid $W/(m \cdot K)$
- $h_c$: mean surface heat transfer coefficient $W/(m^2 \cdot K)$

Figure 17 shows that for the same thermal difference and the same wire diameter, the heat diffusion for liquid hydrogen is twice as good as for Fl15 because of the difference in thermal conductivity between the two liquids. In spite of this, the two liquids are roughly comparable, as the thermal gradient could be three times larger in Fl15 to get the same effect. We thus have to conclude that the big difference in the time needed for the tracks to disappear completely in both liquids is mainly due to the quantity of heat to be diffused. This could be tied to the fast bubble growth in Fl15 compared to liquid hydrogen at operating points.

This very preliminary study will be continued by looking into the growth and recompression of bubbles together with heat diffusion for several liquids$^9$.

5. FUTURE PLANS

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

1) Several modifications to the bubble chamber and its operating conditions will be tried out, with a view to finding more favourable conditions from our point of view: e.g. an expansion system with an added membrane, different operating liquids, higher working temperature, active mixing of the liquid, etc. The higher working temperature, in particular, is expected to provide some improvement. Indeed at a higher temperature 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.
2) 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.

We will test these improvements in February and March 1982 in a test beam at the PS. If the tests are successful we will apply for beam time at the SPS next summer.

In the meantime, HOBC could also be available for testing different holographic ideas for other experiments.

Acknowledgements

We are indebted to A. Quiard-Marigny, D. Güsewell, A. Minten and E. Pauli for their continuous interest and support and we would like to thank, in particular, J.L. Bénichou, A. Didona, G. Merighi, K. Rogers, H. Stiquel and J. Verneois for their competence and enthusiasm during the construction and running of HOBC.

We want also to recognize the importance of the advice given to us by W. Birr.

* * *

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Fig. 1 Chamber body showing two large apertures for the optics windows and two small ones for the beam windows

Fig. 2 Stainless-steel bellows

Fig. 3 Expansion piston showing inner heat exchanger
Fig. 4 HOBC installed at the CERN SPS. The camera is at the back.

Fig. 5 P-T diagram for Freon F115, showing the minimum pressure reached as a function of temperature.
Figs. 6-10  Track evolution as a function of laser delay
Figs. 11-14 Track evolution as a function of laser delay
Fig. 15 Optical index variation with temperature for F115

Gr·Pr = \frac{c_p \rho^2 g \beta \Delta T D_o^3}{\mu k}

<table>
<thead>
<tr>
<th></th>
<th>F115</th>
<th>H_2</th>
</tr>
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<tbody>
<tr>
<td>\rho</td>
<td>1156</td>
<td>57</td>
</tr>
<tr>
<td>\beta</td>
<td>5.8 \times 10^{-3}</td>
<td>4.7 \times 10^{-2}</td>
</tr>
<tr>
<td>\mu</td>
<td>10^{-3}</td>
<td>8 \times 10^{-6}</td>
</tr>
<tr>
<td>c_p</td>
<td>1190</td>
<td>1750</td>
</tr>
<tr>
<td>k</td>
<td>0.076</td>
<td>0.138</td>
</tr>
</tbody>
</table>
| Gr·Pr (For \Delta T = 1 \text{ K}
and D_o = 1 \text{ mm}) | 1.2 \times 10^3 | 2.4 \times 10^3 |
| Nu = \frac{h_c D}{k} | 5.88 | 7 |

\frac{h_c (F115)}{h_c (H_2)} = 0.46

Fig. 16 Optical index variation with temperature for liquid hydrogen

Fig. 17 Comparison of heat transfer coefficient for the wire model for liquid hydrogen and F115
HOLOGRAPHY IN A FREON BUBBLE CHAMBER: 
PRELIMINARY RESULTS FROM THE NA25 EXPERIMENT AT CERN

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1. INTRODUCTION

After the successful holographic test with the Berne Infinitesimal Bubble Chamber (BIBC) in June 1980\(^1\), the next step was to investigate the possibilities of holographic techniques in a real physics experiment. This experiment, NA25, used a freon rapid-cycling holographic bubble chamber (HOBC) as a vertex detector, placed in front of a muon filter providing a trigger for single or dimuon events\(^2\). After some tests in a PS beam in the summer of 1981, the run took place in October 1981 in the H2 beam of the SPS. Although some problems of heat dissipation in freon limited the expansion rate of the bubble chamber, more than 11000 holograms were taken, showing 10 μm bubble tracks, with very good image quality and contrast. More than 100 tracks can be stored on a hologram without affecting the quality if all the bubbles are small. In addition, the analysis of the holograms does not look more complex than the exploitation of conventional high-resolution pictures.

2. THE FIRST OPTICAL SET-UP

The bubble chamber was designed in such a way as to allow the maximum flexibility from the optics side. Direct illumination is possible through two optical windows covering an optical volume of 11 × 5 cm\(^2\) by 6 cm in depth. More details are given in Hervé's contribution to this conference\(^3\).

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) 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 μm. 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\(^4\).

v) The contrast, although slightly worse than for the two-beam set-up, is still very high (much 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 (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 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 in such a way as 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

3. **EFFECT OF TURBULENCE: MODIFICATION OF THE OPTICAL SET-UP**

The first holograms showed that the picture quality had a dramatic dependence on the turbulence in the chamber. As it is obvious that it is hopeless to obtain pictures of 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\(^1\). 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 gives also 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\(^6,7\). The obvious solution is to reduce the distance of the object to the hologram. As this was not possible in our case, owing to mechanical constraints, we decided to use a relay lens of very good quality\(^5\) and to take a hologram of the image of the bubbles 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\(^6,9\). The new optical set-up is shown in Fig. 2. With this system the distance from the centre of the HOB to the hologram has been artificially reduced from 12.5 cm to 4 cm.

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

\(^*)\) This lens was a spare lens of the ERASME system lent to us by H. Anders.
impressive contrast have been obtained with a laser delay of 3 μs. The reconstructed bubble size measured with a microscope was 10 μm (full width above the background). The intrinsic resolution of the system is probably higher than 10 μm, as the bubbles appear round-shaped and sharp (Fig. 3). With a delay of 1 μs, 5 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 to 7 μm.

The 3 μs delay was finally chosen for the data taking. Under these conditions 10,000 holograms with an event trigger and 1150 holograms with a muon trigger have been taken with a bubble density of 200 bubbles/cm for the beam tracks.

Unfortunately the expansion rate of the bubble chamber had to be limited to about 1 Hz. This frequency was imposed by the time needed to evacuate the heat left in the liquid after the bubble recompression which was causing turbulent channels. More details on this problem are given in Ref. 3. 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 with a kicker magnet which had a leak rate of a few per cent. At fluxes in excess of 10⁶ particles per second, the probability was high of having a few very old tracks. In the vicinity of these tracks the image quality becomes poor as can be seen in Figs. 4 and 5: in Fig. 4 an event with 10 μm bubbles is still analysable close to a 80 μm old track. In Fig. 5 another event with 10 μm bubbles is hardly visible close to a 200 μm track. However, more than 100 tracks have been stored on some holograms without kicker leaks. 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.

5. CONCLUSIONS

The NA25 experiment was an occasion to prove that holography is a very attractive technique for experiments requiring the optimum resolution around the vertex. A 10 μm two-track resolution was easily obtained with very good contrast. The problem of the heat dissipation of recompressed bubbles limited by a large factor the number of holograms taken during the run. However, there is some hope of curing this by changing the operating conditions of the chamber. On the other hand, this effect is probably much less critical in other liquids like hydrogen.

Another advantage of holography is to have the maximum resolution in the full volume in 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 shows that holograms are not more difficult to analyse than classical optics high-resolution pictures. Of course the optics of the scanning and measuring machine must be carefully set up in order to exploit the maximum quality of the holograms, which is in general very good. For instance, on an optical bench a r.m.s. of 20 μm was measured for the position in depth of 10 μm bubbles.

The BIBC test proved that good holograms can be taken in a bubble chamber. The NA25 experiment has proved that holography is a very powerful technique which is now ready for use in very high resolution physics experiments.
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Fig. 1 Optical set-up at the PS beam
Fig. 2 Optical set-up for the data taking with the afocal system.

Fig. 3 Typical event with 10 μm bubbles. The picture length is 2 mm.
Fig. 4 Event with 10 \( \mu \text{m} \) bubbles close to an old 80 \( \mu \text{m} \) track

Fig. 5 Event with 10 \( \mu \text{m} \) bubbles close to an old 200 \( \mu \text{m} \) track
TESTS OF SCOTCHLITE HOLOGRAPHY IN THE RAPID-CYCLING BUBBLE CHAMBER

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Among several possibilities for a holographic set-up in the rapid-cycling bubble chamber (RCBC), the simplest one is probably to use RCBC as it is, with the Scotchlite as a reflector, and without modifying the optical ports (Fig. 1). The aim of this report is to investigate the possibilities and the limitations of this approach. Another set-up, based on a concave mirror on the piston head, is described elsewhere in these Proceedings.

Scotchlite can be considered as a diffusing screen because the retroreflected light illuminates the whole surface of the optical window.

In the case of diffuse illumination holography, the limit of resolution is given by the aperture of the optical system, as it is for any set-up. However the contrast is also an important parameter for the image quality, and for diffuse holography it is well known that it can be dramatically affected by the speckle.

This speckle appears as a granularity on the image; the speckle size and the contrast are given by only the smallest numerical aperture of the system at the registration or at the reconstruction of the hologram. Hence to improve the visual quality of the image, a filtering method has to be applied in order to reject all the undesired spatial frequencies corresponding to the speckle, as shown in Fig. 2. This filtering can be done by

i) optical treatment with a filter in the Fourier plane of the replaying system;
ii) electronic treatment at the level of the TV camera of the replaying system;
iii) computing treatment by the convolution of the digitalized image with a mask.

It is clear that the theoretical resolution limit which is related to the speckle size must be better by a factor of 2 or 3 than the required resolution. Therefore to increase the numerical aperture, a lens is used in the set-up, as shown in Fig. 3.

For a 50 mm film without a lens the aperture is limited to

\[ a_1 = \frac{\phi}{2 \times D} = \frac{50 \text{ mm}}{2 \times 2 \text{ m}} = 12.5 \text{ mrad} \]

which gives a spatial frequency cut-off

\[ p_1 = \frac{\lambda}{a_1} = 40 \mu\text{m} \]

corresponding to the speckle size. This means for the object a maximum resolution that is 2 or 3 times worse:

\[ p_1(s) = 100 \mu\text{m} \]

which is unacceptable.

With a lens having a pupil as large as is allowed by the dimension of the RCBC's light port:
\[ \alpha_2 = \frac{150 \text{ mm}}{2 \times 2 \text{ m}} = 37 \text{ mrad} , \]

\[ \rho_2 = \frac{\lambda}{\alpha_2} = 13 \text{ \mu m} , \]

\[ \rho_2^{(s)} = 30 \text{ \mu m} . \]

According to these numbers, 30 \mu m to 50 \mu m bubbles should be seen with a reasonable contrast over the whole field of RCBC. The same lens also acts as a collimator for the reference beam (Fig. 1). The angle \( \theta \) between the object and the reference beam is 0\(^\circ\) on this figure, as for in-line holography. This has the advantage of suppressing the astigmatism, which is very difficult to avoid for two-beam holography, as we have seen and as pointed out by several authors\(^6\).

It must be noted that this astigmatism could be reduced with the film plane perpendicular to the bisector of the angle between the reference and the object beams (second set-up of Fig. 4), as it is very often caused by the shrinkage of the emulsion during processing.

For a first test at the beginning of 1982, an AERO-EKTAR lens will be used, having a pupil of 120 mm and a focal length of 305 mm. This gives

\[ \alpha_3 = 30 \text{ mrad} , \]

\[ \rho_3 = 17 \text{ \mu m} , \]

\[ \rho_3^{(s)} = 40 \text{ \mu m} , \]

\[ \text{demagnification} = 7 . \]

Although this lens is not optimized for our purpose, it will be probably good enough to test the feasibility and the limits of the method.

CONCLUSION

A resolution of 30-50 \mu m seems possible in a holographic version of RCBC, without any modifications to the chamber itself. Some tests are of course needed, and it is foreseen that these will be carried out in the near future.

***

REFERENCES

1) R. Sekulin and E. Miranda, these Proceedings.
Fig. 1 Scotchlite holography set-up

Fig. 2 Speckle in holography
Fig. 3  Fourier filtering

With astigmatism

Without astigmatism

Fig. 4  Double-beam holography

\[ \gamma = \frac{e}{e'} \] shrinkage coefficient

Fig. 5  Shrinkage of emulsion
1. INTRODUCTION

The main hardware ingredients of the NA25 experiment are a heavy-liquid bubble chamber equipped for holography (HOBC) and a muon detector.

In HOBC the charm decays should be detected with a much higher efficiency than in more classical bubble chambers, mainly because of the increased spatial resolution. An improved pattern recognition possibility does not, however, depend only on the resolution, but also on the bubble density. The first holographic test with a bubble chamber filled with freon$^1$ showed that high bubble densities (about 300 bubbles per centimetre) could be obtained.

With a one-muon trigger, the charm signal-to-background ratio is improved by a factor of about 15, which results in a rather small number of holograms to scan.

A sample of 75 holograms has been scanned on the CERN holographic scanning and measuring machine (HOLMES). The first, very preliminary results are discussed below.

The bubble chamber HOBC, the holographic set-up, and the scanning table HOLMES are described in detail elsewhere in this volume.

2. THE FIRST CHARM CANDIDATES

In a heavy liquid the topology alone is not a sufficient signature of a decay, as a secondary interaction with a neutron can give rise to the same kind of topology. However, the secondary activities which show clear evaporation tracks (slow protons) are uniquely identified as secondary interactions. For a charm candidate we demand two secondary activities, neither of them showing evaporation tracks. Up to now, two events out of thirty-five interactions seen in the bubble chamber fulfil this criterion. All four secondary activities are compatible with particle decays. The so-called transverse decay length is shown and described in Fig. 1. Both events fulfill the selection criterion used in the NA16 experiment, namely that the transverse decay length should be inferior to 0.6 mm.

In Fig. 2 is shown a photograph of a part of the event containing the charm candidates. The neutral decay into four charged particles is seen, but the charged particle decay into three charged particles is outside the photograph in the very forward direction.

Even though these events look very much like charm events, more of them have to be studied in great detail before one can be completely sure of their origin.

3. CONCLUSIONS

We have observed two charm candidates in HOBC. It is demonstrated that small transverse decay lengths can be detected under realistic data-taking and scanning conditions using the holographic technique.
REFERENCE


\[ \theta_p \quad \text{Production angle} \]
\[ L \quad \text{Decay length} \]
\[ L \sin \theta_p \quad \text{Transverse decay length} \]

**Fig. 1**

- Very preliminary measurements
  - Shaded: charged decay
  - Open: neutral decay

Bar chart showing:
- 1 event at 0.1 mm
- 2 events at 0.2 mm
- 1 event at 0.4 mm
- 1 event at 0.5 mm
- 1 event at 0.6 mm
- 1 event at 0.7 mm
THE RAPID-CYCLING HYDROGEN BUBBLE CHAMBER HOLEBC

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CERN, Geneva, Switzerland.

Since three years we have been designing, constructing, and operating hydrogen bubble chambers as vertex detectors for charm physics in hadron beams. Experience tells us that this kind of physics requires

- a visual detector technique with spatial resolution well below 50 μm in order to
detect charm decays;
- a detection sensitivity in the nanobarn range;
- unambiguous discrimination between secondary interactions and particle decays.

The best compromise for such a vertex detector is provided by a rapid-cycling (to achieve the required sensitivity) hydrogen (no topological ambiguities) bubble chamber with high spatial resolution. Therefore, the principal design considerations must take into account the formation of small bubbles of correspondingly high density along the tracks. This asks for expansion cycles which are close to the foam limit of hydrogen. To achieve this goal, we need a clean bubble chamber without any seals, which could favour parasitic boiling.

To realize such a clean hydrogen chamber, we decided to construct its body entirely from plastic material. For photography this material must be transparent to visible light, and in order to perform several tens of millions of short expansion cycles it must possess high impact strength to resist the severe shocks caused by the high-expansion accelerations. From all plastic materials available, only the thermoplastic polycarbonate Lexan offers such properties and it is therefore used for the construction of the chamber body. The different parts of the body (optics windows, expansion membrane) are glued together by applying a solvent cementing technique, which provides the required vacuum-tight joints of high structural integrity with smooth edges.

After the first type of chamber, called LEBC, which used one optics window and retro-directive bright-field illumination, a second type of clean chamber, called HOLEBC, was designed in the autumn of 1980. The principal new design features are as follows (see Figs. 1a and 1b):

- Two optics windows for straight-through exposures, which allow for holography as well as for classical bright-field or dark-field optics.
- Consequently, the expansion membrane is now located at the bottom of the chamber. It is driven by a vertically moving piston, which is cooled by liquid hydrogen to prevent any heat input via the piston rod.

After a few preliminary tests at the CERN Proton Synchrotron (PS) we operated such a chamber at the Super Proton Synchrotron (SPS) between 24 October and 2 November 1981.
Chamber operating conditions

- Hydrogen temperature: 29.3 K
- Hydrogen static pressure: 8.3 bar
- Expansion pressure minimum: 4.0 bar
- Piston stroke: 0.7 mm
- Duration of expansion cycle: 4 ms
- Expansion cycling rate: 30 s⁻¹

During this test run, pictures were taken in different optical arrangements:

- Classical optics:
  - Bright field
  - Dark field

- Holography:
  - In line (Gabor type)
  - Separated reference beam

The holographic exposures are described in detail by Sekulin in these proceedings. Examples of classical bright-field and dark-field photographs are presented in Figs. 2 and 3, respectively. Bubble densities between 120 cm⁻¹ and 160 cm⁻¹ were achieved. To determine the resolved bubble diameters, we scanned across the bubble images on bright-field film with a microdensitometer. A typical scan along a track is displayed in Fig. 4. It shows the excellent contrast with density variations of about one between bubbles and background. The measured full width at half maximum across the bubble images is around 20 μm, and two bubbles, with 23 μm distance between their centres, are clearly resolved.

Parameters for classical optics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective lenses</td>
<td>Schneider Componon S</td>
</tr>
<tr>
<td>Focal length</td>
<td>350 mm</td>
</tr>
<tr>
<td>Demagnification (m)</td>
<td>1:1</td>
</tr>
<tr>
<td>Wavelength (λ) of flash illumination</td>
<td>515 ± 10 nm</td>
</tr>
<tr>
<td>Lens apertures</td>
<td>F/11, F/13, F/16</td>
</tr>
<tr>
<td>Nominal spatial resolutions</td>
<td>14, 17, 21 μm</td>
</tr>
<tr>
<td>Nominal depth of focus</td>
<td>1.0, 1.5, 2.2 mm</td>
</tr>
<tr>
<td>Flash delay or bubble growth time</td>
<td>70, 120, 170 μm</td>
</tr>
<tr>
<td>Corresponding bubble diameters</td>
<td>17, 22, 27 μm</td>
</tr>
</tbody>
</table>

During this test-run, we experienced some unpleasant optical distortions caused by turbulences in the liquid hydrogen of the bubble chamber. In general, the chamber liquid is the main source of trouble for any optical system. Consequently, the operation of the bubble chamber and its design concept are crucial for the achievement of decent pictures of events, and this is particularly true for holographic exposures. It might therefore be worth while to recall some basic aspects of this problem.

All bubble chambers suffer from static (via thermal conduction and radiation) or dynamic (parasitic boiling during the expansion cycles) heat loads. In HOLEBC we succeeded in reducing the dynamic heat load as well as the conductive heat flux to a negligible amount. Nevertheless, we are still left with the heat, which is radiated via the optical channels, absorbed in the chamber windows, and finally transferred to the liquid hydrogen.
In hydrogen, heat transport by thermal conduction is too small by several orders of magnitude to maintain an equilibrium between heat input and consecutive cooling. Therefore we are left with turbulent convections, to transport the absorbed heat to the heat exchanger at the top of the chamber volume. Consequently, small volumes of liquid (so-called eddies), with temperatures slightly different from the temperature of the bulk liquid, will move up or down because of the resulting buoyancy. These eddies, with linear dimensions between 1 and 3 mm, deviate light-rays by an angle $\alpha$, which is proportional to

$$\alpha = \frac{\Delta n}{n} \Delta \theta \sqrt{T \frac{L}{n}} ,$$

where $L$ is the distance from the bubble to the wet side of the optics window, $L$ is the linear eddy dimension, $n = 1.1$ is the refractive index of hydrogen, and $\Delta n = 4.2 \times 10^{-3}$ (K$^{-1}$) is its temperature dependence around 29 K [for comparison: in water at 20 °C, $\Delta n = 9 \times 10^{-5}$ (K$^{-1}$)]. Finally, $\Delta \theta$ is the average temperature variation within the liquid. This angle $\alpha$ causes a linear displacement $x$ at the chamber window, which is proportional to

$$x = \frac{\Delta n}{n} \Delta \theta \frac{L^{3/2}}{\sqrt{L}} ,$$

For hydrogen at 29 K we obtain [see Thomas$^2$] and Reinhard$^3$]

$$x \approx 10^2 H^{7/6} L^{3/2} \mu \text{m} ,$$

with $H$ (W·cm$^{-2}$) being the heat flux density through the bubble chamber.

Now, the heat flux density depends on the geometrical cross-section of the bubble chamber and hence in some way on its surface-to-volume ratio. This ratio is of course extremely unfavourable for a small chamber such as HOLEBC, which contains only two litres of liquid. In order to remain in the region of a few mW·cm$^{-2}$ for the heat flux density $H$, we must keep the heat load for HOLEBC below 0.5 W. Then the displacement $x$ of the light-ray amounts to about 5 $\mu$m.

**REFERENCES**

1) R. Sekulin, these Proceedings, p.


Fig. 4
HOLOGRAPHY WITH HOLEBC

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1. INTRODUCTION

The increasing demands of high resolution optics for bubble chamber physics, in order to see the decaying tracks of short-lived particles, led in 1979 to the realization that holography had a distinct advantage, in principle, over conventional optics in the solution of this problem: It is possible to decouple the achievable resolution from the depth of field. Since that time considerable effort has been applied both to testing various types of holographic optics, and to the design of bubble chambers suitable for use with holography. Two small rapid cycling bubble chambers, HOLEBC and NOBC, are now at the stage of initial operations. This paper describes the current status and prospects of HOLEBC, a small (2.5 m) hydrogen bubble chamber designed for operation in hadron beams, to be used in conjunction with the EHS spectrometer, which was tested successfully with both classical and holographic optics in Oct-Nov 1981. The chamber itself and the results with classical optics are described in a separate report to this Workshop[1].

The main aim of this report is to present and discuss the results obtained with holographic optics in HOLEBC in the recent test. Before this, however, a brief summary is given of the laboratory tests made in preparation for experimental runs. This review will serve partly to describe the optical configurations tried in the test, and partly to give some idea of the quality of hologram which it is hoped might ultimately be obtained.

2. TESTS OF HOLOGRAPHIC OPTICS FOR HOLEBC

At the time of the Rutherford Meeting on Bubble Chamber Holography[2] in January 1981, systematic series of tests had been made by groups both at RAL and CERN of in-line holography in the HOLEBC configuration, mainly using wires as targets. The results of these tests are reported in the Proceedings of the Rutherford Meeting[3,4]; they were sufficiently encouraging that one could envisage doing physics with \( \nu \) 10 \( \mu \)m resolution in a real chamber.

Also reported in the Proceedings are the first results of tests of 2-beam holography in configurations similar to that of HOLEBC. The RAL group[5] applied a converging object beam geometry to HOLEBC in which unscattered object light was stopped by a spatial filter just before the photographic plate so as to create dark-field conditions. Results with excellent contrast were obtained. Bjelkhagen[6] also obtained beautiful results with a 2-beam geometry but he used the large-angle scattering from wires, which is a somewhat impractical arrangement for HOLEBC.

The optical configurations corresponding to simple in-line holography and converging beam 2-beam holography are shown in figures 1a and 1b as they would be applied to HOLEBC. In figure 1b, showing the 2-beam optics, the final reference beam mirror which deflects light onto the recording medium lies above the plane containing the object beam axis and the particle beam. Thus the reference light falls on the photographic plate at \( \sim 20^\circ \).
During Spring 1981 further tests of both these schemes were made, including a very systematic series of tests by the Stockholm group\textsuperscript{7).}

A possible modification which could be applied to either the in-line or 2-beam schemes was suggested shortly afterwards in a report by R. Bizzarri\textsuperscript{8).} This is to use an afocal system to transport the image of the bubble chamber to a point more remote from the chamber. Its application to HOLEBC holography is shown in figures lc (for the in-line configuration) and ld (for the 2-beam dark-field holography). This scheme, by removing the image to a point clear of the bubble chamber vacuum tank, makes it possible to place the camera closer to the image, and hence improve the resolution\textsuperscript{*}. Also, for in-line holography, the object and reference beam light paths become more equal, thus minimising the effect of turbulence on the reference light. For 2-beam holography, dark-field conditions can still be achieved, but with parallel illumination of the bubble chamber, by placing the object beam stop at the focal point of the afocal doublet.

This scheme was successfully employed with in-line holography with HOLEBC, using a wide aperture lens from the CERN "Erasme" measuring machine, and is reported in this Workshop\textsuperscript{10).}

Some examples of simple in-line and 2-beam tests with wires, taken at RAL, are shown in figure 2. The results of laboratory tests may be summarised as follows:

1) Resolution of $\lesssim 10 \mu m$ is obtained.
2) Objects of size $\lesssim 5 \mu m$ are easily seen.
3) The signal to background ratio is quite good in the in-line configuration, and excellent in the 2-beam configuration.
4) Some degradation of quality occurs when disturbing media (lexan, turbulent liquids etc) are placed in the beam path, but the results are still acceptable.
5) Satisfactory in-line holograms are obtained with 5% obscuration of the reference light.

All these results are very encouraging, and it was clear by early 1981 that a test of holography in a small rapid cycling hydrogen bubble chamber should be carried out at the earliest opportunity.

3. RESULTS OF THE EXPERIMENTAL TEST WITH HOLEBC

A test was carried out in HOLEBC in November 1981. The chamber\textsuperscript{1) was designed and built by H. Leutz and his collaborators, and ran without problem at 30 Hz throughout the test. The bubble density was kept fixed at $\sim 100 \text{ cm}^{-1}$; no attempt was made to increase this during the test. A 250 GeV/c proton beam entered the bubble chamber; a beam trigger or an interaction trigger was available. The chamber design had not been optimised for

\[ R = \frac{1.54\lambda}{\theta}, \]

where $\theta$ is the angle subtended by the object at the limiting aperture in the system. For lensless holography $\theta \sim$ size of hologram/Distance of hologram.

\textsuperscript{* The resolution corresponding to the Rayleigh criterion is given in coherent illumination\textsuperscript{5) by}
holographic optics, and during the run there was a substantial degree of turbulence in the liquid. It is confidently believed that this can be eliminated in the future.

Tests were made by members of the NA26 collaboration* using 3 of the 4 optical configurations shown in figure 1:

In-line holography with afocal image transport system:
Some tens of plates (10E56) and ~ 20 m 10E56 film were taken.

2-beam holography with afocal system:
Some tens of plates (8E56) were taken.

2-beam converging beam system:
About 100 plates (10E56 and 8E56) were taken.

In the tests, the flash delay was varied in order to try to see bubbles of different sizes, (though the isolation of in-time tracks from old tracks is rather difficult) and some tests were run with the beam flux much higher than the normal 20 - 20 tracks per spill.

Some results of the tests are shown in figures 3 - 7. In all cases these pictures were obtained from polaroids taken from a TV monitor displaying a section of the reconstructed hologram. Rather than refer the reader to figure captions, the contents of these pictures is summarised here:

Fig 3a is a low magnification view of a 2-prong event from an in-line hologram. The bubble size is ~ 25 μm. The hologram was reconstructed by transporting the real image of the event onto the vidicon with a lens, and spatially filtering the signal at the focus of the lens. This method greatly improves the signal to background ratio in reconstruction of in-line holograms.

Figs 3b and 3c are high magnification views of tracks in the same event.

Fig 4 is a high magnification view of a multiprong event from an in-line hologram. The bubble size is ~ 10 μm.

Fig 5a is a low magnification view of a section of the chamber from an in-line hologram taken with more than 100 beam tracks entering the chamber. Spatial filtering of the image has been used. This filtered image could be scanned quite well when projected onto a 1 m x 1 m screen.

Fig 5b is a high magnification view from a similar hologram with high particle beam flux. Two tracks can be seen in focus. (No spatial filtering has been used in this case.)

Figs 6a and 6b are high magnification views of tracks from 2-beam holograms using the afocal image transport system. The bubble size is ~ 30 μm.

* The personnel involved were

CERN: P. Lecoq, P. Olivier, E. Wiatrowski
Oxford: S. Colwill
Rutherford: C. Fisher, E. Miranda, R. Sekulin
Stockholm: H. Bjelkhagen
Fig 7 shows results from 2-beam converging beam holograms:

- Fig 7a is a track with 20 \( \mu \)m bubbles.
- Fig 7b shows a far side fiducial mark,
- and Fig 7c shows a track with 10 \( \mu \)m bubbles in high magnification.

Finally, Fig 7d is a dark-field picture from HOLEBC using classical optics, into which a holographic section (the dark section at the bottom of the picture) of the same magnification has been "spliced". The white bar indicates 1 mm in the chamber.

4. DISCUSSION

4.1 Comments on the optical results

In general the results obtained in this first test of holography in a hydrogen bubble chamber are very promising. The following detailed comments may be made:

a) Resolved bubbles of size \( \sim 10 \mu \)m have been seen with both in-line and 2-beam illumination.

b) The signal-to-noise ratio with 2-beam illumination is not as good as had been expected from the results of laboratory tests. This is largely due to trivial factors which were not optimized during the run (e.g. lack of anti-reflection coating on some lenses, possible back-reflections from the beam stop, and hence possible mis-match in the object to reference beam ratio). Also, a considerable degree of astigmatism is observed in some of the images; this needs investigation.

It is clear that a further test is needed before the ultimate quality of either in-line or 2-beam holograms can be assessed. However, since the aim of using holography is to see decays of short-lived particles in a relatively large volume of the bubble chamber, the decision on the optical configuration to be adopted will depend on such parameters as resolution, contrast, ease of finding the event (i.e. low-magnification scanning requirements), clarity of the image in the vertex region etc.

4.2 Physics prospects for HOLEBC

HOLEBC is a device offering unique possibilities; it has proven itself as a rapid cycling bubble chamber operating at 30 Hz; it uses hydrogen as a target, thus avoiding the problems of heavy liquid chambers in distinguishing decays from secondary interactions, and it is well matched for use with the EHS spectrometer which has excellent coverage of momentum analysis and particle identification. It is very probably that after one further test run it will be able to take holographic data with resolution of \( \sim 10 \mu \)m and with the capability of accepting particle beam fluxes in excess of 100 tracks per pulse. The experiments which may be performed in HOLEBC can be divided into two classes: Those which exploit the high resolution obtainable with HOLEBC, but not its high flux capabilities, and those which exploit both of these features to perform experiments of very high sensitivity.

HOLEBC should be ready to do experiments of the first type using the full power of the EHS spectrometer for downstream analysis, in 1982. Its most likely use will be with K\(^+\) or photon beams, where the ability to use a substantial depth in the bubble chamber is
necessitated by features of the incoming beam. (The enriched K* beam for EHS, has a depth, \( \sim 4\) mm, which is considerably greater than the depth of field corresponding to a resolution of 20 \( \mu \)m in classical optics). In the case of a Bremsstrahlung photon beam for EHS, the full depth of the bubble chamber will be needed to avoid the confusion which would arise from the pair production background if it were confined to the classical depth of field.

Experiments with incident \( \pi, p \) or \( \bar{p} \) beams, which can be well-collimated into a depth of 1 or 2 mm, are likely to remain the domain of classical optics, although in principle holography can gain a factor of \( >2 \) in resolution over classical optics - (20 \( \mu \)m has been obtained in HOLEBC with classical optics, and so far 10 \( \mu \)m bubbles have been used with holography) - and hence a factor of \( \sim 2 \) in detection efficiency could be obtained for typical charmed particle lifetimes. These remarks apply at least when the aim is to see decays of particles with lifetime \( \sim 3.10^{-13} \) secs or greater, and the sensitivity aimed at is of the order of a few events/\( \mu \)b.

The most exciting physics possibilities for HOLEBC, however, remain those which exploit its high flux capability to perform experiments of high sensitivity. For instance, a sensitivity of 1 ev/\( \mu \)b in a typical 10 day run at the SPS requires a chamber cycling at 30 Hz and a flux of several hundred incoming particles per chamber pulse. Two problems must be solved before such experiments can be performed: First (and by far the most important), a suitable trigger must be found. In the case of charm production, considerable effort is currently being expended to devise a trigger suited for use with a spectrometer of the EHS type. The second requirement is to devise modifications to some elements of the EHS spectrometer which will enable them to operate in conditions of higher flux.

5. CONCLUSIONS

With the results of the test run in HOLEBC in November 1981, the fundamental questions of using a small rapid cycling hydrogen bubble chamber in conjunction with holographic optics have been successfully answered.

Certain technical questions remain, and in particular a decision must be made as to the optical configuration which will be used in a physics run. It is very likely that a further test run with HOLEBC will enable the ultimate quality of both in-line and of the various 2-beam configurations to be assessed both in terms of resolution and of picture quality. As far as the bubble chamber operation is concerned, it must be ascertained that the chamber can run without severe turbulence, and an attempt should be made to run with somewhat higher bubble density.

It is hoped that this test can be performed as soon as possible, and that the first physics data with holographic optics in HOLEBC will be taken in 1982.
REFERENCES

1. H. Leutz, invited talk at this Workshop.


4. P. Lecoq and P. Olivier, ibid. p94.

5. C.M. Fisher et al, ibid. p181
   C.M. Fisher et al, ibid. p203.

6. H. Bjelkhagen, ibid. p68.


9. See, for example, Born and Wolf, "Principles of Optics", Section 8.63.

10. P. Lecoq, invited talk at this Workshop.
Fig. 1a Schematic of simple in-line holography for HOLEBC

Fig. 1b 2-beam dark-field converging beam holography for HOLEBC

Fig. 1c In-line holography for HOLEBC with image transport system

Fig. 1d Beam holography for HOLEBC with image transport system
Fig. 2a Two 10 μm wires reconstructed from an in-line hologram

Fig. 2b A 10 μm wire reconstructed from a 2-beam dark-field hologram

Fig. 2 Holograms of wires taken in the laboratory

Fig. 3a In-line hologram from HOLEBC, showing a 2-prong event (or θ-ray) in low magnification

Fig. 3b High magnification view of the event of a)

Fig. 3c The two tracks from the same event. The bubbles are measured to have diameter 25 μm.
Fig. 5. Low and high magnification reconstruction from holograms in NLC. The bubble size is measured to be 10 μm and the picture shows a 1.3 mm section of the bubble chamber.
Fig. 6 Tracks reconstructed from 2-beam dark-field holograms in HOLEBC using an afocal image transport system. The bubble size is measured to be \( \sim 30 \mu m \).
Fig. 7a Tracks reconstructed from a 2-beam dark-field converging beam hologram in MOLBEC. The bubble size is measured to be \( \sim 20 \, \mu \text{m} \).

Fig. 7b Far-side fiducial mark reconstructed from a similar hologram to that of Fig. 7a.
Fig. 7c Track reconstructed from a 2-beam dark-field converging beam hologram in HOLEBC. The bubble size is measured to be \( \approx 10 \) \( \mu \)m and a section of the chamber \( \approx 1 \) mm in length is shown.

Fig. 7d Dark-field photograph of HOLEBC using classical optics. The darker section at the centre-bottom of the picture is from a "spliced-in" dark-field hologram with the same magnification. The white bar represents 1 mm in the chamber.
One of the main limitations in the use of lenses to make images of the bubbles of tracks is the relation between resolution and depth of field (fig. 1)

\[ R = 0.62 \sqrt{2\lambda \delta}, \]

where

- \( \lambda \) is the wavelength of light -- we shall assume \( \lambda = 0.5 \ \mu m \),
- \( R \) is the minimum distance between resolved point objects,
- \( \delta \) is the half-depth of field,

both \( R \) and \( \delta \) being defined according to the Rayleigh criterion.

Three questions can be asked about this relation:

a) Is it good enough for our physical problems?
b) Can we do as well as it says?
c) Can we do better?

a) *Is it good enough?* With hadronic SPS beams and with known charmed particles the answer is yes. For instance, the \( 72 \) beam can have at the EHS position a horizontal focus with an r.m.s. spread of 0.7 mm. Figure 2 shows the fraction of the beam which is in focus as a function of \( \delta \); for \( \delta = 1 \ mm \) 80% of the beam will be useful.

As for the resolution, the "known" charmed particles have mean lifetimes in the range \( (2-10) \times 10^{-13} \) s, corresponding to \( c \tau = 60-300 \ \mu m \). A value of \( R = 20 \ \mu m \) is adequate to detect them with good efficiency.

A useful working point is therefore around \( R \approx 20 \ \mu m \) and \( \delta = 1 \ mm \) (see Fig. 1).

b) *Can we do that well?* Yes. A resolution of 20 \( \mu m \) requires a lens with a numerical aperture of \( \approx 0.015 \) and -- with a demagnification \( m = 1 \) -- an f-number \( f/a = 16 \). It is not too difficult to design such a lens to be diffraction-limited, provided in the design proper care is taken to correct for the effect of the bubble-chamber and vacuum-tank windows.

Working with \( m = 1 \) the film resolution will not be a problem since the cut-off spatial frequency of the pupil is \( a/\lambda p = 1.22/R = 61 \ mm^{-1} \), i.e. in a region where the usual bubble-chamber films have a good modulation transfer function.

c) *Can we do better?* Perhaps. It has been suggested by Welford\(^1\) that an annular pupil be used, with an obstruction ratio \( \epsilon \) (see Fig. 3) to increase the depth of field for a given resolution, or to increase the resolution for a given depth of field. For a constant depth of field

\[ a \approx \frac{1}{\sqrt{1-\epsilon^2}} \quad \text{and} \quad R \approx \frac{1}{a} \approx \frac{1}{\sqrt{1-\epsilon^2}}. \]

An obstruction ratio \( \epsilon = 0.8 \) could allow an increase of the aperture \( a \) by a factor of 1.67 and therefore a resolution of 10 \( \mu m \) could be reached still maintaining \( \delta = \pm 1 \ mm \). Of course, such a pupil would give very bad results for extended objects but the above arguments remain valid for bubble diameters near the resolution limit\(^2\).
At this point a further question could be asked: if classical optics is so good, why worry about holography? There are many good reasons:

i) One might want to use different and less conventional beams which require a larger depth of field.

ii) The search for other particles with possibly shorter lifetimes (b,γ) might make it necessary to aim for a higher resolution.

iii) Holography can allow much higher fluxes of particles in the bubble chamber, thus making possible higher sensitivities if a suitable trigger for the interesting events can be found.

However, for the immediate future classical optics is still going to provide us with very interesting physics.

** REFERENCES **


![Graph](image1)

** Fig. 1 ** Half-depth of field $\delta$ versus the resolution $R$. A possible working point is indicated.

![Graph](image2)

** Fig. 2 ** Fraction of the beam in focus versus the half-depth of field $\delta$

![Diagram](image3)

** Fig. 3 ** Sketch of an annular pupil: the outer diameter is $a$ and the inner diameter $\varepsilon a$
DYE LASER LIGHT FOR HIGH-RESOLUTION CLASSICAL PHOTOGRAPHY

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1. INTRODUCTION

The test run with the bubble chamber HOLEBC in October 1981 offered the opportunity of checking the usefulness of de-speckled dye laser light for illumination purposes in high-resolution classical dark field photography of small bubble chambers. More detailed information about the photographic arrangement of HOLEBC is presented by H. Leutz in these proceedings. First results from experiments to destroy the coherence of dye laser light were reported at the second EHS workshop in Vézelay, in March 1980 1). Further work on this subject will be briefly presented here.

2. LASER

The dye laser used for these illumination tests was a home-made laboratory model, based on a 25 kV two-stage Marx driver and a simple (no water cooling) 60 J coaxial flash lamp (Candela Corp.) incorporating a 5 mm diameter dye cuvette of 150 mm length. The FWHM of the light pulse is 150 ns.

3. CAVITY

The 80 cm long resonating cavity was built in a plane-plane mirror configuration for broad-band output. The reflectivity of the output mirror was set at 60% in order to obtain maximum spectral width of the laser light.

4. DYE

Coumarin-522 was used in an ethanolic solution of $2 \times 10^{-3}$ mol/l concentration. The dye has a moderate output efficiency of about 0.3, compared with Rhodamin 6 G which is often taken as an output standard. 53 J electrical discharge energy yielded an output energy of 33 mJ.

5. REPETITION RATE

The repetition rate was 6 pulses/min at lower output energies (< 5 mJ) and 2 pulses/min at higher energies. The reduction in rate is due mainly to the absence of water cooling, since in the case of the simple lamps the discharge heat stored in the quartz envelope of the discharge lamp has to be removed by the circulating dye solution. With modern quadrax flash lamps repetition rates of up to 5 Hz are possible.

6. DE-SPECKLING ELEMENTS

50 m of PCS quartz monofibre QSF 1500 C with a 1.5 mm diameter core served a twofold purpose: to allow a great distance between laser and bubble chamber and to de-speckle the dye laser light. This arrangement was very effective: only a 60 cm long quartz rod was still needed to remove entirely the granularity of the laser light. The promising results will stimulate further development of this interesting subject.
7. **SET-UP**

Figure 1 outlines the set-up. A thin quartz plate is used to reflect 7% of the light beam onto a joulemeter. Appropriate neutral density filters are used to protect the joulemeter from damage and also to vary the light energy according to the photographic system under consideration.

The two principal arrangements of classical photography are sketched in Fig. 2. Bright field photography is shown in Fig. 2a, while Fig. 2b shows the dark field arrangement of HOLEBC, the average scattering angle being 6°. The energies needed to illuminate these two arrangements are quite impressive: in bright field photography 0.05 mJ of pulse energy at the input end of the fibre (its losses were not measured) were sufficient to obtain an optical density D_{opt} \sim 1.0, while dark field photography in HOLEBC needed 25-30 mJ for acceptable density of the bubble images on the film.

8. **POSSIBLE APPLICATIONS**

The dye laser provides very high spectral energy density (expressed in mJ/mm), enabling

- spectral decoupling of each of several photographic channels, serving different purposes at different times during the expansion cycle of a bubble chamber;

- fast light pulses, 120-150 ns FWHM (even linear flash lamp-pumped medium to high energy dye lasers hardly go beyond 2 \( \mu \)s pulse width, while excimer laser-pumped dye lasers have only 10-15 ns pulse width);

- efficient focusing into quartz fibres and thus energy transport over large distances, owing to the small divergence of the laser beam.

**REFERENCE**

Fig. 1

DYE LASER
COUMARIN 522
Δλ: 5-10 nm

1mm quartz plate
N.D. filters
Joulemeter
60 cm quartz rod
10 mm Φ
Fibre optic scatter plate

50 m
QSF 1500

Fig. 2

Film plane
Lens F=360 mm
Condenser lens
Scatter plate

Film plane
Objective lenses
Condenser lens
HOLEBC
THE FUTURE PROGRAM OF CHARM PHYSICS WITH THE EHS APPLICATIONS OF HOLEBC AND THE RCBC

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1. INTRODUCTION

I started preparing this paper with a view to examining specifically the possibilities of developing the RCBC for charm physics. It quickly became clear however that it is timely to review the whole of the EHS high resolution program and to discuss the evolution of the spectrometer without prejudice to the vertex arrangement. This I will briefly attempt to do. The physics possibilities are extremely exciting and we will see that both HOLEBC and a suitably developed RCBC system have different regions of application in which they excel. A prime objective of this paper is to define the regions of technical development that, in my opinion, should be pursued in the next year and to indicate the physics return that might follow in the future.

It should be remembered that the essential components of the EHS, including the RCBC, were designed for physics in 1973/4. The design was based on an overall optimisation of the set up to give as complete an analysis as possible of hadronic interactions over the full kinematic range i.e. \(-1 \leq x_F \leq +1\), for incident momenta up to \(\sim 400\) GeV/c. The matching between RCBC, MI and the downstream spectrometer is based on general kinematic conditions and error analyses and has not therefore changed. In 1974 SLAC and FERMILAB discovered the \(\psi/J\) and "charm" was born experimentally. In 1975 we realised that it should be possible to detect and study the charmed hadrons using a high resolution bubble chamber, and this has been demonstrated using LEBC in NA13 and NA16 (1979, 1980). We must now consider the possibility of developing the RCBC (and if necessary other components of the spectrometer), or changing the vertex arrangement, to allow the direct study of charmed particle production and decay. I will try to answer the following questions in this talk:

i) Since we have shown with NA16 that we can detect charmed particle decay vertices using the high resolution hydrogen chambers LEBC and now of course HOLEBC, why is it interesting to consider the RCBC?

ii) If we are to consider RCBC for high resolution physics, what resolution do we need to achieve to be useful and what kind of experimental program can be foreseen.

To answer these questions it is first necessary to look briefly at the physics we will be trying to do and what information is needed to provide useful data.

2. PHYSICS WITH CHARM AND BEAUTY AT THE EHS

The physics that we are in principle able to study can be stated briefly as follows:

(a) Particle lifetime measurements for which we need length measurement plus reconstructed momenta on an unambiguously identified sample of events.

(b) Mass determinations for some (rare!) states. Clearly absolute mass determinations can only be made for events with identified unambiguous decay modes and having precise and absolute momentum measurements.
(c) Particle decay modes. With the exception of the simple decay modes of the D-mesons little is known and much has to be done in this area. In particular the study of Cabibbo favoured versus non-favoured decays for all ground state particles plus the measurement of leptonic and semi-leptonic branching ratios is crucial to the theoretical understanding of the decay mechanisms and is correlated to the questions of lifetime differences.

Experimentally we know from SPEAR that the decay modes are in general complex, involving strange particle plus pions, with a mean multiplicity of \( \mu \approx 4 \) for the charmed mesons. Charmed baryons will of course have the additional problem of having a baryon, which could be strange, in the final state. The importance of particle identification cannot be overstated particularly when low branching ratio Cabibbo unfavoured decays have to be established unambiguously.

The fact that the EHS is a very complete spectrometer providing both precisely measured momenta and particle identification puts us in a unique situation for the detailed study of charm decay physics in the future.

It should be noted that the above topics require a reasonable sample of unambiguously identified decays. There is no dependence on production mechanisms and to a first approximation, problems arising from the spectrometer acceptance can be corrected by simple weighting procedures depending only on phase space calculations in the decay process.

(d) Production mechanisms in proton induced reactions.

Two fundamental questions have to be answered and again the EHS is probably uniquely suited to do so.

i) To understand the mechanism and S-dependence of the cross section for the production of the \( \Lambda_c^+ \) particle. The ISR data indicates large cross sections (300 - 1500 \( \mu \text{b} \)) depending on the assumed rapidity distribution. The data favours a flat \( y \)-distribution suggesting a high cross section with a significant diffractive contribution. At SPS energies, where \( \sqrt{s} \) is down by only a factor 2.5, the only evidence for \( \Lambda_c^+ \) production comes from NA11 (75 \pm 50 \( \mu \text{b} \)). It is very important that we find the \( \Lambda_c^+ \) signal directly to study both the decay and the production mechanism in p-p.

ii) To understand the beam-dump data. The beam dump is a complex indirect method of detecting charmed particle production in p-Cu, Fe interactions. Cross section estimates have varied from 100 - 200 \( \mu \text{b} \) for inclusive D production in 1978-79 to \( \sim 10 - 30 \mu \text{b} \) for the same process in 1980-81. Differences come partly from statistics but more importantly from changes in the interpretation - linear A dependence or \( A^{2/3} \), \( x_F \) distribution at production .... etc. Direct measurement of the production \( x_F \) distributions in hydrogen for each particle i.e. D, F, \( \Lambda_c^+ \), plus their leptonic or semi leptonic branching ratios, is crucial to the interpretation of this data. The EHS can provide this information. It is then possible to ask if the total beam dump signal can be explained by charm production and decay or if some new process or particle must be invoked.
(e) Production mechanisms in pion or kaon induced reactions.

It is important to compare meson induced reactions with proton induced because of the presence of a valence antiquark in the pion (or kaon) and hence the possibility to have charm production via a quark annihilation mechanism. A comparison between the $x_F$ distribution and cross section for charm production in $\pi^-p$, $K^-p$, $p\overline{p}$ and $\overline{p}p$ can help to understand the relative contributions from the quark annihilation ($q\overline{q}$), quark-gluon, ($qg$) and gluon gluon ($gg$) mechanisms. The particular interest in kaon induced processes obviously follows from the fact that the antiquark (or quark) in the Kaon is strange and hence can be followed to the final state. Moreover we expect high cross sections for the production of F-mesons which are particularly interesting in their decay properties.

(f) Photoproduction of charm.

Photoproduction is obviously exciting because it has the possibility of a relatively high charmed particle yield from a "simple" hadronic final state trigger. It is well suited to the study of charm decay properties and possibly to the threshold production and detection of beauty. This is the motivation of the Photoproduction Letter of Intent II40.

3. CONDITIONS TO BE MET BY THE SPECTROMETER

From the above considerations it is clear that the physics program is both extensive and exciting provided that the spectrometer can give the relevant data. The following conditions must be met experimentally:

(a) Good high resolution vertex detection. This is the essential feature that distinguishes our technique and spectrometer from all others and is an enormous advantage. At its lowest level direct vertex detection provides a clean highly efficient off line trigger on charm. If the spectrometer is subsequently considered only as a "counter set up" with a hydrogen target this alone provides a background rejection factor of a thousand to one - admittedly at some considerable cost in effective data rate! Vertex detection however does considerably more than that. The correct association of outgoing tracks to their vertex of origin reduces, indeed in the case of zero topological ambiguity removes, the combinatorial problem amongst charged particles in the final state (given particle identification - see later).

Since we are in general dealing with highly complex events; a pair of charmed decays with a mean additional charged particle multiplicity of 10 or 12, the above considerations are paramount. In addition however direct vertex detection provides a measurement of the decay length which is essential for lifetime determination.

The need for high resolution is clear, we will discuss how high and the implications for RCBC in the next section, however for the physics described above it is not yet enough! High resolution is a necessary condition but is not in itself sufficient to study the charm and beauty physics of interest.

(b) Charged particle momentum and angle measurements.

Clearly, for any purpose of reconstruction, precise measurements of charged particle
momenta are required. The original design of the EHS was optimised to minimise the error on effective mass calculations between pairs of particles emerging from interactions in the RCBC. This defines the field in M1 and the position and resolution required in the spectrometer planes, and also the specification of the second lever arm, beginning with M2. The whole is optimised to give resolution typically in the range 10–20 MeV at the mass of a D-meson i.e. $\approx 2$ GeV/c² over the whole momentum range to 400 GeV/c². NA16 has shown that the performance in practice is in agreement with the design specification (see Alan Poppleton's talk). Typical charged particle momentum errors are $\approx 1\%$ and angle errors at the vertex are $\approx 0.1–0.2$ mrad.

In considering the charm questions the important differences that arise between an RCBC experiment and, for example HOLEBC upstream of M1 in the NA26 arrangement, come from the acceptance variations. The RCBC situation is optimal in that momenta and angles are well determined from the lowest momenta (few MeV/c) seen in the bubble chamber (by range) to the maximum momentum of the SPS. Since the detection efficiency for the charm decays in the chamber does not depend strongly on the momentum of the charmed particle it is important, if we wish to reconstruct charm produced at all $x_F$ and with a variety of beams, that the decay products are well measured over as large momentum range as possible. For NA16 for example the acceptance was only good for D mesons produced in 360 GeV interactions with $x_F$ positive and this is in general true for any arrangement like NA26 (or NA16'), having HOLEBC upstream of M1 in a "field free" position.

(c) Particle identification.

The identification of charged particles from charm decays is crucial to any future charm experiment. The EHS system in principle spans the full momentum range using ionisation in the bubble chamber (RCBC), SAD, ISIS, PC and TRD. The full spectrometer should be operational in 1982 and its performance in this respect should make it unique amongst fixed target spectrometers. The importance for charm studies has already been evaluated in the previous section.

(d) Neutral particle detection.

Most charm decay modes involve final state $\pi^0$, $\eta^0$ mesons. The IGD and FGD are designed to maximise the acceptance for gammas from $\pi^0$'s produced at $+ve$ $x_F$. NA16 has demonstrated the value of $\pi^0$ detection for charm reconstruction. Precision on the $\gamma\gamma$ effective mass is typically 15 MeV/c² (FWHM) and on the reconstructed $\pi^0$ momentum $\approx$ few%.

For the future the neutral particle detection will be completed by the addition of the FNC and INC - the neutral hadron calorimeters. These again will be of great value for charm physics because of the importance of $K^0_L$ and sometimes $\eta$, $\bar{\eta}$ in the decays. Again acceptance is optimised for a production vertex at the centre of M1.
4. **THE DETECTION OF CHARMED PARTICLE DECAY VERTICES: WHAT RESOLUTION IS NEEDED?**

The method and resolution needed to detect decay vertices was studied, at first using Monte Carlo generated events, by Robert Sekulin, Dave Crennell and myself. Subsequent experience with NA13 and NA16 has shown that the ideas are substantially correct and the problem well understood. Two levels of detection can be identified:

i) To show that an interesting decay has occurred in an event and therefore that the event can be selected as containing charm or some other short lived decay and;

ii) To clearly see the decay vertex and hence correctly associate all the charged particles with their vertex of origin.

Clearly ii) requires better resolution than i). The parameters that determine the visibility of a decay are illustrated in Figure 1; they are the decay length \( L \), the transverse decay length \( x \) and the maximum impact parameter \( y_{\text{max}} \) of charged secondaries from the decay.

![Diagram of decay vertices](image)

**FIG 1.**

In the absence of other charged particles in the event it is only the decay length \( L \) that determines the visibility of the decay and it is only necessary that the resolution be significantly better than \( L \). This is the situation near threshold; for example in the SLAC photoproduction experiment (see the proposal RL BCG Physics Note 122, C Fisher 1979). At high energies the presence of many additional charged particles from the production vertex (typically 10–12 at 300 GeV) seriously confuses the problem and the resolution required is considerably higher than at low energies. We discuss this situation now:

To show that a decay has occurred in the event we must find one track or more that does not point back to the primary vertex i.e. having a significant impact parameter \( <y> \) compared with the experimental resolution. We have:

\[
y = L \sin \theta_{\text{decay}}
\]

We can write

\[
y = \frac{p_y}{\sqrt{p_{11}^2 + E^*}} \cdot \tau_c
\]

where \( p_y, p_{11} \) and \( E^* \) refer to the decay product in the rest system of the charmed particle,
$\tau_c$ is the actual lifetime multiplied by $c$ and $\beta$ is the velocity of the charmed particle in the lab in units of $c$. In the approximation $\beta \approx 1$ we have $\gamma_{\text{max}} = \tau_{\text{max}} \sqrt{c}$ where $\gamma$ depends only on the decay kinematics. The value of $\gamma$ is estimated using a Monte Carlo assuming a phase space distribution for the decay products in the $D$ decay for any given mode. We use the best available (SPEAR) data on the decay modes and average over all decay modes to find the probability that $\gamma_{\text{max}}$ in a decay exceeds some value, say twice the experimental resolution, and hence that the event is detected. The result of this Monte Carlo analysis, is shown in Figure 2.

![Graph showing efficiency vs. mean lifetime](image)

*Fig. 2* Monte Carlo estimate of the efficiency to detect $D$-meson decays by requirement that $\gamma_{\text{max}} > 100 \, \mu\text{m}$ - NA13 result

An important feature of this analysis is clearly that the detection efficiency, i.e. the values of $\gamma$ in the decay, depends only very weakly (through $\beta$) on the momentum of the charmed particle, i.e. essentially does not depend on the beam momentum or the $x_F$ at production. We are therefore well placed to study production mechanisms.

It is also a simple matter given the Monte Carlo detection efficiency for a given lifetime or resolution to derive the detection efficiency, using the impact parameter technique, for any other lifetime or resolution.

Consider now the question of the clear detection of the decay vertex i.e. a visible vertex separated from other final state particles in the event. The important parameter is now $x$ the transverse decay length

$$x = L \sin^2 \theta_{\text{prod}} = \frac{p_{\chi}}{m} \frac{p_{\chi}}{p_D}$$

$$x = \frac{p_{\chi}}{m c} \cdot \tau_c$$

Thus $x$ depends only on the transverse momentum at production and the lifetime. Note again that $x$ is a transverse decay length and therefore does not depend on the beam momentum or
the $x_F$ production. Two consequences follow from this simple expression:

i) That for charmed particle decays we expect $\tau \lesssim 2 \times 10^{-12}$ secs and $p_L \% mc$ so that $x \lesssim 600$ $\mu$m. Thus all decay vertices are expected to be within 600 $\mu$m of the forward direction independent of the momentum of the $D$, and hence the decay length $L$ (which can easily be several centimetres). Thus we have the idea of a charm box containing all decay vertices.

![Charm Box Diagram]

ii) In general we expect $p_L < mc$; typically $\frac{p_L}{mc} \sim 1/5$. The probability that the decay vertex is clearly resolved can only be estimated by Monte Carlo, this time depending on the production distribution of the additional particles in the event.

In Table 1 we give the results of the decay impact parameter Monte Carlo analysis for various interesting lifetimes and resolutions.

<table>
<thead>
<tr>
<th>Resolution lifetime</th>
<th>5 $\mu$m</th>
<th>20 $\mu$m</th>
<th>40 - 50 $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-12}$ secs</td>
<td>94%</td>
<td>82%</td>
<td>64%</td>
</tr>
<tr>
<td>$3.10^{-13}$ secs</td>
<td>84%</td>
<td>50%</td>
<td>20%</td>
</tr>
<tr>
<td>$1.10^{-13}$ secs</td>
<td>59%</td>
<td>12.5%</td>
<td>1%</td>
</tr>
<tr>
<td>$5.10^{-14}$ secs</td>
<td>35%</td>
<td>1.5%</td>
<td>-</td>
</tr>
</tbody>
</table>

The efficiency for clear vertex detection is of course considerably less and depends on the production mechanism and associated complexity of the event. As a rule of thumb! divide by two or three! The third column represents approximately the condition for NA6, the second (20 $\mu$m) the expected performance for HOLEBC (NA6') and the third (5 $\mu$m) the ultimate (?) expected from holographic HOLEBC.

The following conclusions can be drawn:

(a) Any future charm experiment must have a detector with resolution better that NA6 - however for charm studies in general we are sensitive to and can usefully study charm production and decay using a detector with resolution 30 - 40 $\mu$m. This would be a realistic aim for a large chamber such as RCEC which has the considerable analysis advantages discussed above.

(b) Classical HOLEBC (NA6') should give us excellent data on charm decay properties and
production in the forward direction. Clear vertex detection should be considerably better than in NA16.

(c) Holographic HOLEBC must be seriously pursued. It offers the only real possibility of reaching lifetimes of interest for Beauty (with the possible exception of threshold production where the cross section is likely to be too small to access). The other advantages of holography - in particular the increase in depth of field and hence cross section sensitivity is also critical to such future experiments which clearly require very high sensitivity and a selective charm trigger.

5. CONCLUSIONS

The conclusions I wish to emphasise are the following:

(a) The physics of charm requires not only high resolution but also good acceptance for the decay products of charm particles by the spectrometer.

(b) The EHS is very well matched to the problem because of the complete nature of the analysis of individual events that is possible.

(c) The acceptance properties however are matched by design to the RCBC i.e. having the production vertex at the centre of M1. RCBC also, because of its volume and conventional views, provides an essential component of the spectrometer for low energy tracks which would normally be outside of the acceptance. This will include particles from charm decays and in many cases associated particles from D* decays etc.

RCBC with a resolution $\gtrsim 20$ μm would be ideal. RCBC with a resolution $\lesssim 40$ μm would be an excellent chamber for charm studies and could combine the charm physics with a general soft physics program.

(d) HOLEBC is of course also excellent for direct charm detection: two developments are recommended:

i) To consider the possibility of putting HOLEBC inside M1 to improve acceptance - alternatively to significantly increase the M1 gap keeping HOLEBC in its NA26 position. This would allow much improved charm studies however it might be necessary to augment HOLEBC with additional detectors inside M1 (streamer chamber).

ii) To fully develop holography with HOLEBC. This is essential for a future charm program based on prompt triggering. The study of Beauty production and decay will clearly depend critically on having a holographic HOLEBC coupled with a suitable trigger. Note that such an experiment may also need modifications to the EHS to cope with rate limitations and possibly also to improve acceptance.

Thus high on the list of technical developments, at the vertex region, for our future charm physics program I would put:

(a) Holography with HOLEBC.

(b) High resolution optics (classical and (or) holographic) for RCBC (running at 30 – 40 μm).
(c) Triggering on charm (not discussed here but see the talk of Sven Olaf Holmgren).

(d) Possible modifications of M1 - increase the gap(?). Streamer chamber(?) etc.

Many other considerations are relevant, for example obviously the acceptance question becomes more severe as the beam momentum is reduced if the vertex is not situated in M1. Quantitative estimates of these effects are in progress or will be done via Monte Carlo studies, for future experiments. High on the list of desirable features is of course the detection of strange particle decays occurring close to the production vertex as well as downstream in the spectrometer.

It is important in 1982 that both the technical questions and limitations referred to above be explored and that suitable Monte Carlo studies are completed to evaluate quantitatively the advantages and disadvantages of the various options.
HIGH RESOLUTION WITH RCBC USING CLASSICAL OPTICS

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ABSTRACT
A brief assessment of the possibility of a classical optical system for RCBC to give a resolution of better than 50 microns is presented. Reference is made to the tests made in RCBC during August 1981 and to the system installed on the 40 inch SLAC chamber.

1. INTRODUCTION

At Vezelay, last year\(^1\) I suggested that a resolution of better than 50\(\mu\) might be achieved in RCBC. This was provided that attention was paid to the design of a suitable lens system with corrections for the chamber and vacuum tank windows, and the liquid hydrogen. I also placed emphasis on the choice of film and the image size in particular with regard to the maintenance of image contrast.

The prediction was also based on the assumption that image broadening due to thermal turbulence in the liquid hydrogen would not contribute more than 10\(\mu\) to the apparent bubble size.

Since the Vezelay meeting RCBC has become operational. Also we have carried out some simple photographic tests to examine the high resolution potential of the chamber.

During this same period work at SLAC on the 40 inch chamber has progressed from exploratory tests\(^2\) to successful high resolution experiments.

This paper discusses the performance of RCBC with particular reference to the high resolution tests, compares the results of these tests with the performance of the SLAC system and proposes an initial high resolution system for RCBC.

2. HIGH RESOLUTION TESTS IN RCBC

Calculations of the effects of thermal turbulence in RCBC have been made for a lens of focal length 480mm and show a significant loss of contrast for relatively small heat fluxes (\(\approx\) a few milliwatts/cm\(^2\)) through the liquid hydrogen. Such heat fluxes are difficult to measure so that photographic tests were considered to be necessary.

Observation of the chamber during operation both by eye and by noting the movements of a laser beam reflected from a mirror on the fiducial ring indicated very low thermal turbulence except for a region close to the top of the chamber near to the main heat exchanger. These favourable indications were not altogether surprising since considerable attention had been paid to supression of nucleate boiling by controlling the heat fluxes into the chamber.

In order to obtain more direct evidence of magnitude of thermal turbulence some photographic tests were carried out before the main N23 physics run this summer, using the camera system developed by Dr Hans Anders for checking the Optical Fiducial Volume Trigger.
This system consists of a 35mm camera back with a 500mm focal length Componon-S lens. The flash illumination system is similar to that of the main RCBC cameras but has a short duration of 60 microseconds and is filtered to allow the use of light in the spectral range 600-700 nanometers.

The demagnification is 5.3:1 so that a region 129mm x 191mm along the beam direction in the beam entry side of the chamber is seen through the small window at the beam exit side. The angle of view ranges from 8 to 15° so that the effects of astigmatism, dispersion and field curvature produced by the windows are not negligible, nor indeed is the lens performance diffraction limited.

A high resolution, fine grain film, Kodak Technical Pan 2415, was used.

In order to give a satisfactory bubble density and moderate bubble growth rates the operating temperature of the chamber was raised to 27.20K.

The focus was set by photographing a 150 micron diameter wire, stretched across the chamber in the beam plane. Photographs were taken with the chamber cold (at 600K) and full of gas, and during operation at 5Hz and 27.20K over a range of expanded pressures and growth times with apertures set at f/8 and f/11.

A simple examination of the MTF curves for the film - lens combination for the average field angle of 11.5° suggests a resolution at f/11 in the range 75-100 microns, (MTF = 0.075). This ignores the aberrations introduced by the windows and the liquid hydrogen which give astigmatism of ~ 15 microns, dispersion of ~ 25-50 microns and field curvature of ~ 2mm over the field of view, again for f/11. The flash duration was short enough for the bubble diameters to increase by only ~ 5 microns during the flash.

Some 200 pictures were taken with the liquid temperature control very stable and with no base heater applied to the chamber. Visual inspection of the tracks show good contrast with no indication of random distortions or variation in contrast associated with thermal turbulence. The systematic optical distortion can be clearly seen in the elongated images.

Measurement of the minimum bubble image diameter is difficult due to the orientation of the tracks with respect to the distortions, since most tracks are from non-interacting beam particles. The same comment applies to the 150 micron diameter wire.

Microdensitometer measurements have been made of both the wire and of tracks.

Figures 1 and 2 show microdensitometer plots of the wire from photographs taken with the chamber full of gas at 600K and with the chamber operating at 27.20K. The plots are virtually identical in all respects and although this is not a very sensitive test does indicate that thermal turbulence is low. The full width at half height for transmission is 148 microns for both plots.

Figure 3 shows a photograph of an event taken at f/11 with bubble diameters in the range 37-47 microns. The track widths measured with a low power microscope vary from 83 to 150 microns depending on the orientation of the track. For the short tertiary track which is most closely aligned with the distortions the microdensitometer plot is shown in Figure 4. The full width at half maximum transmission is 85 microns.
Microscope measurements made of the wire on the same view show a width of 159 microns at one end and 190 microns at the other end.

These results are consistent with the expected lens - film performance and the various aberrations, but unfortunately do not demonstrate clearly the potential of the chamber since the allowable effect of thermal turbulence is of the same order or less than the effects of the optical system. Subjectively, the absence of any detectable signs of thermal turbulence, and the good contrast are very encouraging.

3. PROGRESS AT SLAC WITH THE 40 INCH CHAMBER

The early tests at SLAC\(^1\) showed acceptable contrast for track widths in the range 65 to 70 microns using a system based on a Schneider Componon-S lens of 360mm focal length with an aperture setting of f/11. Various films were used with a filtered flash illumination system having a spectral range of 530-610nm and a duration of 50 microseconds. A higher temperature of 28.5\(^\circ\)K was used and the chamber operated at 10Hz.

Since those tests the system with some modifications, has been used to take photographs for experimental work. The full chamber diameter is photographed onto Kodak 2460 film with a reduced flash duration of 30 microseconds and track widths of 55 microns obtained with the chamber operating at 10Hz\(^2\).

Although the field angle does not exceed 12.5\(^\circ\) for the centrally placed lens, this is a good performance for a commercially available lens system and no doubt owes a lot to the favourable geometry of the system.

4. PROPOSED HIGH RESOLUTION SYSTEM FOR RCBC

Optically a diffraction limited lens fully corrected for the chamber windows should give a resolution of better than 40 microns with a depth field of \(\pm 2mm\)\(^1\). Although the results of the tests in RCBC are not conclusive they are such as to suggest that effects of thermal turbulence are small and not in excess of the assumed 10 microns included in my Vezelay paper, so that a target of 50 microns seems perfectly feasible. The results at SLAC support this view in that without a diffraction limited lens and without correction for the aberrations caused by the windows acceptable track widths of 55 microns are consistently obtained.

It is therefore proposed to build a system for RCBC to the following specification:

- **Lens:** Diffraction limited at f/9, focal length \(\approx 400mm\).
- **Demagnification:** 4:1 to allow track images of 10 micron width at 40 micron track width.
- **Light Source:** Either short duration flash \(\approx 10-20\) microseconds filtered to give spectral range about 500nm of \(\pm 50nm\) or dye laser operating at 500nm.
- **Film:** High resolution, high gamma film such as Kodak 2460 in 50mm format with a frame length of 105mm.
- **Geometry:** Camera to be placed to view the chamber through view one instead of the existing camera 1 and to view a
region 200mm x 420mm along the beam direction, starting inside the fiducial ring.

Although the mechanical design of this system is much simpler than for either of the spare camera ports, the optical design is complicated by the camera and hydrogen shield windows which are tilted through $7^\circ$. It is possible either to introduce two triangular prisms to correct for this or to accept incomplete correction for astigmatism and field curvature (using a laser, dispersion is not present).

* * *

REFERENCES


2) G. Kalmus, REPORT ON BC-73 TEST, (1979).

3) G. Kalmus, (Private Communication).
Fig. 1

Fig. 2
Fig. 4
CLASSICAL HIGH-RESOLUTION OPTICS FOR
THE RAPID-CYCLING BUBBLE CHAMBER - PRACTICAL ASPECTS

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1. INTRODUCTION

The RCBC, as a medium-size bubble chamber (visible volume 80 cm in diameter and 35 cm in depth), is equipped with three "normal" cameras resolving 200 \( \mu \)m bubbles at 1:15 demagnification. It uses a Scotchlite background for bright field illumination, and photographs the bubble tracks through a 17 cm thick cold glass window and smaller double windows in the vacuum tank end-plate at almost 2 m distance from the track plane.

The physics groups preparing experiments with RCBC showed a strong interest in having one or two high-resolution (HR) cameras to complement the normal photographs by more detailed information around the primary interaction. In specifying such a HR channel for RCBC, one has to find an acceptable compromise between visible volume (demagnification), resolution, and depth of field; its implementation must avoid any expensive or risky modification of the existing equipment.

It is evident that a HR channel on a bubble chamber of the size and structure of RCBC is not competitive in resolution with the small, dedicated, high-resolution chambers. The strength of RCBC is in its position in the centre of the main EHS magnet, the good acceptance matching with the spectrometer, and the hydrogen volume around the HR volume visible to the normal cameras and particularly useful for identifying strange particle decays. A HR camera on RCBC will therefore only be interesting in combination with the normal cameras, and it will generally be used only for a qualitative picture scanning. Experience with a similar bubble chamber at SLAC and a study of the different limitations show\(^1\) that nevertheless a compromise performance can be proposed which would seem to be satisfactory for the planned experiments. It is the purpose of this contribution to submit a program for providing a working HR camera by the summer of 1982.

2. SPECIAL LENS

In order to achieve the required resolution of better than 50 \( \mu \)m, a special lens is needed for correcting the window aberrations, in particular the curvature of the field. After a preliminary discussion with one of the potential suppliers, a final tender action is under way, which aims at ordering one or two lenses before end 1981. Delivery can then be expected before the end of July 1982. The following lens specification is proposed:

- Demagnification 4:1; image size 50 \times 105 \text{ mm}^2
- Field of view up to 19° semi-angle
- Curvature of field within ±0.5 \text{ mm}
- Lens design based on use of narrow-band light (incoherent laser source) around 500 nm
- Alternative offers requested for diffraction-limited lenses with f/8 or f/11 full aperture (corresponding to on-axis Airy disk diameters on film of 7 and 9 \( \mu \)m, respectively).
3. **Camera**

A fast film drive (15 Hz) offering the maximum image length (105 mm) acceptable for Bessymatic and ERASME tables, has been developed for HOCBC and HOLEBC2. It is also well suited for RCBC. At a moderate cost (< 20 kSF) such a camera could replace the present camera No. 1 in the main camera port near the beam entry. This solution, however, is not satisfactory as it weakens the normal track reconstruction considerably. In addition, the main ports with their inclined windows give rise to particular correction problems. On both sides of port No. 1 are situated smaller auxiliary ports with untilted windows. Their size is sufficient for use with the above-specified HR lenses. However the associated holes in the external camera plate are too small and the dimensions of the normal camera No. 1 too big to permit easy use of these auxiliary ports. The camera plate has to be modified and camera No. 1 integrated into a new combined support for one normal and one or two HR cameras (cost for first step 60 kSF). If a decision is taken in December 1981, one HR camera can be available for August 1982.

4. **Visible Volume and Fiducial Volume Trigger**

At the proposed demagnification and image size, the HR picture will correspond to a useful volume of $42 \times 20 \times 1$ cm$^3$. It is proposed to position it along the beam for $-32.5 \leq x \leq +10$ cm. It is then seen exclusively against the Scotchlite of the piston. For adjusting the HR lens (and matching, perhaps later, the focal planes of two HR lenses), correcting distortions, and correlating HR and normal views, it is planned to stretch a frame of 100 μm wires; this would provide fiducials in two planes, visible to all cameras.

The usefulness of the HR camera will depend critically on the availability of a specific HR fiducial volume trigger (HRFVT). If we consider interactions over 38 cm of hydrogen as being acceptable on the HR view, only every third interaction trigger should be accepted. The optical fiducial volume trigger (OFVT) could well be matched to the HR fiducial volume, but its decisions could only control the normal cameras; the OFVT requires at least 1 ms for bubble growth, read-out, and decision, whereas the HR camera has to be flashed 100-200 μs after the interaction. Without a good HRFVT, the data rate of RCBC with HR view would be reduced (if camera limited) to 1/3 of its potential rate, and

$$\frac{2/3 \times 3 \times 11.6 \text{ cm}}{3 \times 11.6 + 3 \times 7.6 \text{ cm}} = 40\%$$

of the total film exposed would be useless HR pictures.

There is, however, a good hope that the trigger concept of experiment NA26 and a good part of the special hardware could also be used on RCBC. A decision for a HR camera on RCBC should thus be accompanied by a study program with a view to implementing on RCBC a trigger similar to the NA26 set-up. Only then can the investment in effort and time be justified.

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HOLOGRAPHY IN THE CERN RAPID-CYCLING BUBBLE CHAMBER: PRACTICAL ASPECTS

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The discussion of classical high-resolution cameras for the CERN RCBC showed that a compromise has to be found between resolution and depth of field, which is not fully satisfactory for the envisaged experiments. One probably has to live with a resolution between 40 and 50 μm in order to have a minimum depth between 5 and 10 mm. On the one hand, for experiments with hadronic beams the accent is on resolution; values below 40 μm would be a considerable benefit, if this could be achieved without a noticeable loss of fiducial volume and depth. For photoproduction experiments, on the other hand, the accent will be mainly on depth for reasons of beam optics and event rate.

Ideally, holography promises to decouple resolution and depth. In practice, holography in RCBC will evidently suffer from the same optical constraints -- such as liquid inhomogeneities, thick window aberrations, and low numerical aperture limited by the distance of the warm windows -- which will probably exclude resolutions of better than 40 μm in classical optics. It is thus an open question whether holography, as it stands now, will ever become an interesting way of track recording in RCBC.

In 1982, only a limited effort will be available for RCBC, and it must be devoted mainly to doing the approved experiments under the best conditions, using the existing optics plus, if required, one classical high-resolution camera. However, as the production run of RCBC in the summer of 1982 has to be prepared by a technical run in the spring, we propose to devote a fraction of this technical run to holographic tests in order to determine the potential of holography in RCBC without risk for the "classical" purposes of the run, namely by identifying weak points in more than \(10^6\) expansions, testing a new piston, achieving expansion rates above 20 Hz in good track conditions, and exploring common operating conditions for normal and high-resolution photography. Two schemes for holography in RCBC have been studied, one using the existing Scotchlite as a reflector [Lecoeq et al.\(^1\)] and one using a spherical mirror on the RCBC piston [Sekulin and Miranda\(^2\)]. Whereas the first solution does not require any modification inside RCBC, can be easily combined with the normal cameras, and easily tested using any of the six warm windows, it will only offer a limited resolution, suffering from the imperfections of the Scotchlite as diffuser and from speckle. The mirror solution promises a higher resolution, but requires the technically difficult installation of a huge, good quality, spherical mirror on the piston; it implies many operational risks and makes illumination for the normal cameras very difficult, without providing visibility for the whole RCBC volume. If, despite these restrictions, the mirror solution is considered interesting for an experiment, we propose, for the technical run, to install a small (10 cm Ø) metal mirror on the fiducial ring near the beam exit, pointing to camera port 1 (see Fig. 1). Such a mirror would not greatly influence the natural liquid motion in RCBC, and spurious boiling at its supports would not affect the tests planned with classical high-resolution optics. It should, however, give representative results on the resolution limit achievable, in practice, with holography in RCBC.

In this way, the technical run of RCBC in the spring of 1982 would provide the facts necessary to decide whether a holographic experiment in RCBC is feasible.
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Fig. 1 Proposed arrangement for testing holography with a spherical mirror in RCBC
TESTS ON A HOLOGRAPHIC METHOD FOR THE RAPID CYCLING BUBBLE CHAMBER

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This report describes a preliminary series of tests performed at RAL to investigate the possibility of using holography in RCBC. In these tests the geometry and dimensions of RCBC were reproduced as far as was practicable.

The geometry of RCBC necessitates the use of a reflective illumination system and the 2 choices which present themselves are either to use the Scotchlite which currently covers the RCBC piston, or to replace it with a different reflector. In either case the bubbles would be illuminated in converging light, which leaves the chamber through one of the viewing ports. A separate reference beam would be used, which does not enter the chamber. Apart from the use of Scotchlite, the simplest method for providing a converging object beam is to use a concave mirror, where a diverging source enters the chamber, covers the entire piston area and is directed back towards the recording medium as a converging beam. In this way, the hologram records the same zero angle scattering from bubbles in all parts of the chamber, resulting in a simple, even illumination of bubbles.

With Scotchlite, one port is used both to illuminate and view the chamber, collecting the maximum amount of light retrodirected by the Scotchlite. With the mirror some choice is available, and the use of an axially symmetric setup using two opposite ports, one for illumination and one for viewing would enable the mirror to be used by more than one view.

In the tests carried out at RAL, both Scotchlite and concave mirror illumination were tried. A linearly polarised continuous wave argon ion laser tuned to 514.5 nm was used with Agfa-Gevaert 8E56 plates. A reference to object beam angle of about 20° was chosen with a plane reference wave facilitating the use of the real image on replay. The plate was placed with its normal pointing to the centre of the Scotchlite/mirror, and the reference angle measured with respect to that normal. Wires were used as a test object and no glass was used. The experimental arrangements are shown in figures la) and lb).

In the case of Scotchlite illumination a spatially filtered source was placed about 10 cm from the plate. Although the Scotchlite was not viewed at 0° it still provided bright field conditions.

In the case of mirror illumination, a similar configuration was used but the mirror was tilted to produce a focus 10 cm in front of the plate. A stop was then used to remove all but scattered light, resulting in dark field conditions. Due to the poor quality of the mirror used in the test a very large spot was produced at the focus and it was necessary to use a spatial filter of 25 mm diameter.

The resolution of the system with a plate of height h at distance D from the object is given by

\[ R \approx \frac{1.54 \lambda D}{h} = \frac{1.54 \times 514.5 \text{ nm} \times 1.8 \text{ mm}}{0.1 \text{ mm}} \]

\[ = 14 \mu \text{m} \]
The holograms were replayed by using the same reference beam, turning the plate about face and looking at the real image either directly with a vidicon or using a lens to magnify the real image onto it.

Results of the tests are shown in figures 2 and 3. The coherent illumination on the Scotchlight produces speckle over its surface with a speckle size of the system resolution. As can be seen, the speckle has the effect of swamping images of objects approaching the resolution in size and of generally reducing contrast when compared to incoherent illumination. The location and recognition of wire images at high magnifications was found to be very difficult. The minimum wire size seen was 60 μm, i.e. about 3 to 4 times greater than the system resolution. Thus to see 30 μm bubbles about 8 μm to 12 μm resolution would be needed.

A further problem encountered with Scotchlight is the irregular rotation of the plane of polarisation by the mylar covering, which results in an uneven illumination of the field of view and the loss of images in the darker regions. A possible solution would be to use circularly polarised light, but this remains to be investigated.

With the dark field mirror setup contrast is good, wires being seen over the whole 80 cm diameter. 10 μm wires, though clearly not resolved, are easily visible. 20 μm wires are seen as two parallel lines where the system has resolved the scattering from each edge. The distance between the centres of the two lines is measured to be 20 μm, and each edge has a thickness of about 16 μm.

In conclusion, successful holograms have been made both using Scotchlight and concave mirror illumination. The better results were obtained with concave mirror illumination, where good contrast is obtained, and wires a factor of 3 - 4 times smaller are seen. It would certainly be of great interest to carry out holographic tests in RCBC itself of both of the illuminating systems we have tried.
Fig. 1 RCBC holography geometry with a) Scotchlite, b) dark-field concave mirror
a) Two 125μ wires

b) 60μ wire

Fig. 2 Bright-field Scotchlite scheme
a) 10μ wire, measured width ∼ 16μ

b) 20μ wire

Fig. 3 Dark-field concave mirror scheme
CHOICE OF THE RECORDING ARRANGEMENT FOR BUBBLE CHAMBER HOLOGRAPHY

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ABSTRACT
The main characteristics of the different recording arrangements are compared. The in-line system is the most simple and the cheapest but it does not suit to all types of chambers. The side-band systems yield different sorts of images and require different coherence, stability and energy conditions according to the type of illumination of the bubbles.

INTRODUCTION
The possibility of reconstructing detailed pictures of bubble tracks from a hologram was proved by the BIBC experiment achieved last year at the CERN\(^1\). However this test was carried out in very favourable conditions and it is not evident that it would yield comparable results with an other bubble chamber or in the conditions of an ordinary technical run.

The problem is not only to get one three-dimensional picture but also to obtain a good resolution with a given recording repetition rate. From this point of view it is essential to choose a suitable arrangement as well as the adapted material to record the hologram and to reconstruct the image.

THE IN-LINE SYSTEM
The most practical arrangement for recording holograms of microscopic objects is the in-line system which was imagined by D. Gabor then proposed by Welford to be used in bubble chambers\(^2\). As shown in figure 1 the system needs very few optical elements: the laser beam is merely enlarged by an afocal system to the dimensions of the field then it travels straight through the studied volume to the holographic plate.

![Fig. 1: Schematic diagram of the in-line recording system.](image-url)
It is well known that this system provides images that are free from field aberrations. The spherical aberration is acceptable if the reconstruction wavelength is not too different from the recording wavelength. Moreover no special precaution is needed to fulfill the coherence requirements as far as the hologram is recorded with the help of a monomode laser. This explains why a good image quality was obtained so rapidly in the BIBC tests (fig. 2). Let us also point out that a laser pulse duration of 20 nanoseconds allows the bubbles to move at 100 m/s with no significant degradation of the image.

In fact, various other conditions have to be fulfilled to obtain a good image. As the reference is not separate from the object beam, the object itself has an influence on the quality. Thus it is easy to understand the influence of the bubble concentration\(^3\) and of the index gradients in the chamber: the higher they are, the worse the image. As a consequence, it is important to mention that in a chamber equipped with a unique port,

![Fig. 2: Bubbles of 25 μm reconstructed from the BIBC tests.](image)

the use of a mirror to reflect the incident beam back to the window artificially doubles the bubble concentration and the amount of turbulences.

The front window of the chamber must have a good optical quality but even so it may produce substantial aberrations. Let us take an example. A flat window is perfectly stigmatic for the parallel reference but it produces a slight spherical aberration on the object waves emitted by the bubbles. At contrary, a spherical window is stigmatic for a bubble located at its center but not for the reference.

We have shown that, contrary to side-band holography, the best image/background ratio is obtained at the inflexion of the Hurter-Driffield curve of the emulsion, which corresponds to an optical density of about 1.2 in normal processing conditions (fig. 3). A density variation of 0.5 involves a negligible loss of contrast\(^4\). Moreover it is possible to adjust the processing time and temperature in order to compensate a lack or an excess of energy with a ratio as high as 4.

Because the greatest part of the light emitted by the laser arrives at the hologram, the in-line system is very economical. For example, a pulse of 0.5 millijoule allows a 9 x 12 cm\(^2\) hologram to be recorded on a normally processed 10 E 75 plate.

It is also to be noted that the presence of a high magnetic field in the chamber does not disturb the recording as the reference and the object waves undergo the same modifications. As to the fact that the object-beam/reference ratio cannot be adjusted,
this is not a drawback for bubbles greater than the diffraction limit.

![Graph](image)

Fig. 3

**TWO-BEAM HOLOGRAPHY**

In the side-band system, the reference is separate from the object beam and it may travel out of the chamber. Thus it is not disturbed by the turbulences nor by a high bubble concentration. This allows a greater number of tracks to be recorded simultaneously with a higher amount of turbulences. The effect of these two parameters on the image quality is similar to that obtained with classical photography. This remark also applies to the quality of the windows.

On the other hand, the angle between the two beams generates field aberrations which are more difficult to minimize. The following table was calculated for the two different

![Diagram](image)

Fig. 4
arrangements shown in figure 4: a) The reference inclination is equal to 45° while the object beam is normal to the plate. b) Both beams are inclined at 45°. In each case the recording and reconstruction arrangements are identical except for the wavelengths \( \lambda \) and \( \lambda' \) corresponding to available lasers.

<table>
<thead>
<tr>
<th>Lasers</th>
<th>( \lambda, \lambda' )</th>
<th>sph.abs.</th>
<th>coma</th>
<th>astig.</th>
<th>(( \mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruby He-Ne</td>
<td>6943 6328</td>
<td>0.5</td>
<td>10</td>
<td>5</td>
<td>( \Delta_1 )</td>
</tr>
<tr>
<td>Ruby Kr</td>
<td>6943 6471</td>
<td>0.3</td>
<td>7</td>
<td>2</td>
<td>( \Delta_1 )</td>
</tr>
<tr>
<td>Ruby Kr</td>
<td>6943 6763</td>
<td>0.1</td>
<td>2.5</td>
<td>0.3</td>
<td>( \Delta_1 )</td>
</tr>
<tr>
<td>YAG Ar</td>
<td>5320 5145</td>
<td>0.2</td>
<td>3</td>
<td>0.5</td>
<td>( \Delta_1 )</td>
</tr>
<tr>
<td>YAG Kr</td>
<td>5320 5308</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>( \Delta_1 )</td>
</tr>
</tbody>
</table>

The optical path distortions \( \Delta_1 \) and \( \Delta_2 \) are given in microns*. The first arrangement is obviously more advantageous: not only the field aberrations are smaller but it is also much easier to explore the reconstructed image in this case.

The optimal density of the processed hologram is about 0.3. It corresponds to an exposure twice as small as for the in-line system. In fact, the total energy required for the recording depends on the losses of light in the object, i.e. on the type of illumination. The kind of image (dark or bright field) and the coherence requirements also depend on this parameter.

a) Direct diffuse illumination

The object beam coming from a diffuser (Kodatrace by transmission, Scotchlite by reflection) travels through the chamber straight to the plate [Fig. 5a]. If the diffuser is adapted to the aperture of the system, the losses of light will be moderate. For example, preliminary tests achieved in the geometrical conditions of BEBC have shown that an energy of less than 10 mJ allows a volume of 1 m³ to be recorded on a \( 6 \times 9 \text{ cm}^2 \) plate 5). The tolerance on the optical path difference between the two beams is the same as with an in-line system. The same remarks applies to the eventual velocity of the bubbles. On the other hand, a dark image is reconstructed over a bright background. Thus the most important problem is to eliminate all the extraneous lights in order to have an acceptable image contrast. As a counterpart, the influence of all the turbulences located above the bubbles in the direction of the light beam is completely eliminated.

* For an aperture of 40 mm and an object distance of 200 mm.
b) With a direct, non-diffused illumination, it is necessary to block the non-diffused light to observe the image (fig. 5b). This can be achieved either at the recording or at the reconstruction by putting a schlieren stop on the image of the point source: the image of the bubbles is bright with a dark background. It is to be noted that this system is very sensitive to the chamber turbulences. To eliminate their influence a larger stop is needed, which reduces the energy - and the information - diffracted by the bubbles toward the plate.

c) A lateral illumination of the object (fig. 5c) provides a bright image on a dark background. A diffuser is not useful in this case. As the light diffracted by the bubbles decreases rapidly with the angle of illumination, this method requires much more energy than the preceding (at least 100 to 1000 times, according to the angle and to the bubble size). Moreover the tolerance on the optical path differences are much more severe. For example, an angle of 90° involves that the coherence length of the laser be much larger than the field width.

CONCLUSION

As shown by the BIRC experiment, the in-line system looks well adapted to small bubble chambers with very weak turbulences. A good image contrast and a high resolution are easily obtained with very moderate stability, coherence and energy requirements.

For other chambers we will rather recommend the use of two-beam holography. Direct illumination looks more appropriate as the stability and coherence requirements are less severe than with a lateral illumination. In the latter case the needs of power look prohibitive.
For large chambers it is better to use a lens in order to re-image the bubbles near the holographic plate and to reduce the size of the studied field.

In any case a good image resolution will be obtained only if the reconstruction wavelength is close enough to the recording wavelength. Let us also recall that the resolution can also be limited by the quality of the emulsion substrate. An interferometric study of a glass plate shows thickness variations of the order of one \( \lambda \) per centimeter (fig. 6). Hence a diffraction-limited image will be obtained only with a reduced aperture so that the emulsion be considered optically flat.

![Interferometric study of a 10E75 glass plate.](image)

**Fig. 6**: Interferometric study of a 10E75 glass plate.

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PROBLEMS ON HOLOGRAPHIC IMAGING TECHNIQUE AND ADAPT LASERS FOR BUBBLE CHAMBERS

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ABSTRACT
Different types of holographic recording technique for bubble chambers are presented and compared. The influence of turbulence on resolution is discussed as well as the demand on laser equipment. Experiments on a test model of HOLEBC using a pulsed ruby laser are also presented.

1. INTRODUCTION

The possibility to use holography for bubble chambers was mentioned long ago. Holographic technique applied to small bubble chambers has recently been met with great interest since the resolution capability of ordinary photography has proved to be insufficient for the track recordings needed nowadays.

In-line holography has been taken into consideration mainly because of its simplicity. Two-beam holography has been described and tested in experiments by using a mock bubble chamber simulating a real bubble chamber at CERN (HOLOBC). In-line holograms have been made in a small chamber at CERN.

In this paper an investigation has been performed to show the influence of turbulence on resolution and image quality in holograms recorded in a mock bubble chamber. For this purpose a new test model of a bubble chamber has been made. Both in-line and two-beam recording technique have been used. Apart from the holographic recording technique it is also essential to discuss the laser and the demand on it for bubble chamber recording.

2. HOLOGRAPHIC RECORDING OF A TURBULENT BUBBLE CHAMBER MODEL

2.1 Bubble chamber model

For the turbulence experiments a bubble chamber has been constructed (50mm x 100mm x 150mm). 5 μm wires simulating tracks have been placed in the chamber as well as two resolution targets, one positive and one negative. The chamber was filled with water and it was possible to heat it at the bottom and to cool it at the top to introduce turbulence in the water. In order to create bubbles, the chamber was filled with champagne for some experiments instead of water. The chamber was made of glass, but a piece of lexan (thickness 24 mm) could be placed between the chamber and the holographic plate.

2.2 The experimental arrangement

A two-beam and an in-line set-up have been used according to Figure 1. The test model of the bubble chamber with the two resolution targets is shown in Figure 3. Photographs of the two-beam set-up are shown in Figure 4.
and 5. For the recording a pulsed ruby laser (Holobeam 651, λ = 0.6943 μm, pulse duration 20 ns) has been used. The output energy is up to 150 mJ for TEM₅₀.

The beam was expanded by means of a negative lens (~7mm) and a front lens from a telescope to get a collimated beam 50 mm in diameter. It was split in two beams by a beam splitter (50%/50%) and the penetrating beam was used as the reference beam. It was directed by a black mirror (5%, M₂ in Figure 1) towards the plate. The reflected beam from the beam splitter was used to illuminate the chamber. This beam was focused towards a stop just in front of the plate. The angle between the reference and the object beam was 20°. The output energy from the laser was 80 mJ, due to the beam arrangement and missing optical components to be able to use less output energy. However, the reference beam was only 2 mJ. The object beam was around 40 mJ, though it could be less. The diffraction efficiency would then be reduced. Using the laser at CERN, the reference beam can be 2 mJ and the object beam has to be around 15 - 20 mJ, which can be done with a little different and not so light wasting set-up as the one used here.

For in-line experiments the black mirror (M₂) was used and the beam was just passing through the chamber. Output energy was around 4 mJ. The plate was placed 300 mm in front of the chamber for all the experiments with the two-beam set-up. For in-line tests two different distances were used, 300 mm and 130 mm.

The recording plate emulsion was AGFA 8E75 HD. The evaluation of the holograms has been made by using a collimated laser beam from a 15 mW He-Ne-laser. The real image was enlarged and projected onto the videcone tube of a TV-camera. Photographs of the TV-screen were made showing wires or the resolution target. All the experiments are presented in Table 1.

2.3 Results

The results are presented in form of photographs of the holograms recorded at the TV-monitor. The relation between the performed experiment and Figure number is found in Table 1. Figure 2 is a contact print of an in-line hologram, where the degree of turbulence in the chamber is shown. The resolution targets can also be seen in this Figure. In Figure 6 the resolution of a two-beam hologram recorded at a distance of 300 mm from the chamber, filled with water of room temperature and without lexan, is about 15 - 20 μm. The theoretical resolution at this wavelength and for this set-up is about 5 μm. Note that the reconstruction of the hologram is made with another wavelength than for the recording (0.6328 μm in relation to 0.6943 μm). The resolution can be affected by this difference in wavelength. However, if only a comparison between different holograms is made it does not matter. Figure 7 shows the influence of lexan and Figures 8 - 10 show influence of turbulence. A combination of lexan and turbulence is shown in Figure 11. The resolution is reduced by turbulence but it is very little affected by the lexan plate.
The possibility to record a hologram on film is demonstrated in Figure 13 and Figure 15. The film was fixed to a glass plate by tape during the recording and pressed between two glass plates during the reconstruction. The film seems to be as good as the plates. Figure 16 shows two air bubbles at the wire and two in the water. In Figure 17 some unfocused air bubbles cause interruptions of the wires. Figure 18 shows the quality of the wires in turbulent water and through lexan. Figure 19 and Figure 20 are photographs of the recordings of the chamber filled with champagne showing bubbles, resolution target and wires. Figure 21 - 25 are in-line recordings at a distance of 300 mm between the plate and the chamber. Figure 26 - 29 are in-line holograms at a distance of 130 mm.

The resolution for in-line holograms is very much affected by turbulence. It is an advantage to record the in-line hologram as close as possible to the chamber. No spatial filtering was used in the reconstruction of the in-line holograms to improve the quality, since the aim was to study the influence of turbulence only.

2.4 Comments on turbulence

A two-beam holographic set-up can be used to record holograms of a turbulent chamber, if the turbulence is up to the degree of the turbulence demonstrated in this experiment. In-line holography seems to be difficult to use in a turbulent chamber if the plate cannot be placed very close to the chamber. Therefore, an imaging system that would project an image of the bubbles very close to the recording plane could be of a great advantage. In order to avoid distortions and to get high resolution, the lens system used has to be of a high quality.

3. LASERS FOR HOLOGRAPHIC RECORDINGS OF BUBBLE CHAMBERS

There are not many different types of lasers that can be used for holographic bubble chamber recordings. Firstly, the laser used has to be a pulsed laser and very often a laser with a high pulse repetition rate.

For pulsed holography, in general, there exist mainly two types of solid-state lasers. The most widely used is the ruby laser equipped with a Pockel cell for Q-switched operation, producing light at a wavelength of 0.6943 \( \mu \)m. The laser has to operate in the TEM\(_{00}\) -mode and with a coherence length long enough for the space that is to be recorded holographically. By using an etalon in the cavity the coherence length of 100 – 1000 mm can be obtained. The pulser repetition rate is low. Outputs from a fraction of a joule to tens of joules per pulse are common.

Another type of solid-state pulsed laser is the neodymium YAG – laser with a wavelength of 1.06 \( \mu \)m. If a lithium niobate frequency-doubling crystal is used in the system an output wavelength of 0.53 \( \mu \)m can be obtained. The conversion efficiency of the crystal is low so the output power from the laser has to be high. Outputs from 0.1 to 1 joule are common and pulse repetition rate goes to tens of hertz in such a system. Both solid-state laser systems for holography are rather expensive and there appear problems when trying to obtain stable output performance.
Other types of pulsed lasers are pulsed gas lasers like the nitrogen laser with a wavelength of 0.3371 \textmu m or the excimer-laser which emits light in the ultraviolet part of the spectrum. Such lasers have a high pulse repetition rate and a rather stable output. The output power is, however, lower than that of solid state lasers. Such lasers can be used to pump a dye laser so that any wavelength in the green or red region can be obtained. This sort of system is not as expensive as the solid state laser system, but it has a rather limited output power, especially when a $\text{TEM}_{00}$-mode and long coherence length are wanted. It can be sufficient for small bubble chambers if an in-line recording technique is used, but in the two-beam technique there can be some problems to get enough output power from the system.

An advantage of the dye laser system is that the recordings can be made with a wavelength that is the same as the wavelength of the He-Ne-laser or the Argon laser, depending on which is meant to be used for the scanning and evaluating system for the recorded holograms.

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REFERENCES


### TABLE 1

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- Bubble Chamber with water
- Lexan
- Turbulence
- Champagne (room temperature)
- Plate distance 304 mm
- Plate distance 130 mm
- Film
Fig. 1 Recording arrangement

Fig. 2 Turbulence, contact print of an in-line hologram plate

Fig. 3 Bubble chamber

Fig. 4 Two-beam recording set-up

Fig. 5 Two-beam recording set-up
THE PERFORMANCE OF THE SPECTROMETER FOR NA16

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ABSTRACT

NA16 is an experiment at CERN which used a prototype version of the European Hybrid Spectrometer to reconstruct the decay products of short-lived charm particles produced and decaying in the small high resolution (≈ 50 μm) LExan Bubble Chamber (LEBC). An analysis of approximately 25% of the NA16 data led to results on charm properties presented at the Lisbon Conference on High Energy Physics.

1. INTRODUCTION

The two-lever-arm spectrometer (Fig. 1) provides charged track and γ/π⁰ reconstruction. The first lever arm LA1 follows the magnet M₁ and consists of the six-plane multiwire proportional chamber (MWPC) W₂, a 'small' (2 × 1 m² sensitive area) drift chamber D₄, and two 'large' drift chambers D₂ and D₃ (4 × 2 m²), the pictorial drift chamber ISIS₁ (1.5 × 4 × 2 m³ sensitive volume), and the intermediate γ-detector (IGD). The second lever arm [LA₂ = M₂ + D₁ + D₅ + forward γ-detector (FGD)] improves the momentum precision for charged tracks above ≈ 30 GeV/c and complements the γ-detection. For particles below ≈ 20 GeV/c ISIS₁ provides limited mass identification.

2. ACCEPTANCE

The spectrometer acceptance is limited by the M₁ aperture, which shadows the first lever arm up to D₃. The aperture (100 × 40 cm²) corresponds to an angular acceptance of ≈ 200 × 180 mrad² for tracks originating in LEBC. The IGD dimensions (195 × 160 cm²) correspond to production angles of ≈ 95 × 80 mrad²; the central hole is covered by the FGD, fully in the horizontal direction, but only about 70% vertically. At the NA16 beam momentum (360 GeV/c) particles produced in the forward centre-of-mass hemisphere have a laboratory angle of less than 80 mrad with respect to the beam direction:

\[
\frac{P_L}{P_T} = \frac{\gamma p_L^*}{\gamma E^*}
\]

\[
P_T = \frac{P_T^*}{\gamma}
\]

therefore

\[
\tan^{-1} \left( \frac{P_T}{P_L} \right) < \frac{1}{\gamma} < 80 \text{ mrad}
\]

as 8γ = γ = 13 for π⁺p or pp at 360 GeV/c. Similarly forward hadrons will have lab. momenta ≥ 8γmₚ ≈ 1.8 GeV/c. M₁ can be crudely approximated by a vertical transverse momentum kick of 0.5 GeV/c at 2 m from the vertex, so in the limiting case of a charged pion at rest in the centre of mass the track will leave the spectrometer just after the start of ISIS₁.

Thus the spectrometer should detect all charged tracks and most γ's with xₚ > 0. For events measured satisfying the NA16 scanning criteria, Fig. 2 shows the total number of charged tracks per event, the number reconstructed in the spectrometer (≈ 55%), and the number reaching the second lever arm (≈ 15%). Figure 3 shows the momentum distribution for
tracks reconstructed as far as ISIS, the end of LA1, and using LA2. It is clear that the second lever arm acceptance is well matched to the requirement of improved momentum precision above 30 GeV/c. The tail of fast tracks reconstructed only as far as ISIS is explained by the \( \sim 2\% \) interaction length of ISIS. The limiting effect of the magnet apertures on the acceptance of each lever arm is evident in the dip-angle (angle in non-bending plane) distribution shown in Fig. 4.

3. RESIDUALS + EFFICIENCIES

The position information provided by LEBE is more than an order of magnitude more precise than any other device in the spectrometer; residuals to a straight line fit to track measurements are 8-10 \( \mu \)m in space. Angular precision on tracks is limited to \( \sim 0.1 \) mrad by the precision of fiducial mark measurements, which are required to transform track measurements from the recording medium (film) to the spectrometer coordinate system.

Line-fit residuals in the drift chambers are typically 300-350 \( \mu \)m per plane, except for high inclination tracks where they are significantly worse. Calibration data taken with non-interacting beam tracks show a high efficiency for registering hits outside a region of \( \sim 1 \) mm around each field wire (48 mm wire spacing), with shadowing by other tracks (\( \delta \)-rays in beam data) being the main cause of inefficiency. The electronic dead-time of \( \sim 40 \) ns corresponds to an \( \sim 2 \) mm shadow. Overall single plane efficiencies are 97-98\% for calibration data, but multitrack shadowing reduces this for event data to below 80\% in the most densely populated region before ISIS. Space charge (positive ion) build-up in the beam region causes local reductions in the drift velocity of \( \sim 1\%-2\% \). The precision of an impact reconstructed in a drift chamber (four planes with sense wires at \(-15^\circ, -5^\circ, +5^\circ, +15^\circ \) to the horizontal) is thus about 200 \( \mu \)m (1 \( \mu \)m) in the bending (non-bending) planes.

The MWPC W2 deployed at the start of the spectrometer is less precise (2 mm wire spacing) than a drift chamber, but has an \( \sim 95\% \) single-plane efficiency for beam or event data — although it cannot distinguish the number of tracks responsible for any single hit.

4. MOMENTUM MEASUREMENT

The momentum (\( p \)) of a charged track is measured from its angular deflection (\( \theta \)) in the magnets M\(_1\) (1.5 T\*m field integral gives \( \theta \) \( \sim \) 0.45/p rad/GeV) and M2 (3.0 T\*m gives 0.9/p rad/GeV). The expected angular precision in either lever arm is \( \sim 40 \) \( \mu \)rad from the drift-chamber precision (200 \( \mu \)m) and spacing (5 m); in LEBE it is \( \sim 100 \) \( \mu \)rad. Then

\[
\frac{\Delta p}{p} = \frac{\Delta \theta}{\theta} = 2.2 \times 10^{-4} \quad \text{for} \quad \text{LEBE + LA1}
\]

\[
= 0.44 \times 10^{-4} \quad \text{for} \quad \text{LEBE + LA1 + LA2}.
\]

At the beam momentum (560 GeV/c) LA1 + LA2 give \( \Delta p \leq 8 \) GeV/c; including LEBE measurements should (and does) increase the precision to \( \sim 6 \) GeV/c (as shown in Fig. 5).

Below 120 GeV/c the momentum error is dominated by multiple Coulomb scattering in the various media (the largest contributions are from the bubble-chamber liquid and exit window, ISIS, and air — there is 7\% of a radiation length of air between LEBE and D5)

\[
\Delta \theta \text{ (multiple scattering)} \approx \frac{3}{p} \text{ mrad}
\]

according to distance traversed.
\[
\frac{\Delta p}{p} \sim 0.7\% \quad \text{for} \quad p < 30 \text{ GeV/c (LA1)} \\
\sim 0.6\% \quad \text{for} \quad p < 120 \text{ GeV/c (LA2)}.
\]

The error on the production angle is \(\sim 150 \mu\text{rad} \) for LA1 and \(\sim 60 \mu\text{rad} \) for LA2, with approximately equal contributions from the bending and non-bending planes -- the greater length available for the latter being compensated by the lower bubble- and drift-chamber precision in this direction.

5. **MASS RESOLUTION**

At high energies the effective mass of a multibody system may be expanded, using small-angle and relativistic approximations, into three dominant terms: a constant threshold factor + an 'opening angle' term + an 'asymmetry' term.

For two bodies:

\[
m_{12}^2 = (E_1 + E_2)^2 + (p_1^\star + p_2^\star)^2 \\
= m_1^2 + m_2^2 + 2E_1E_2 - 2p_1p_2 \cos \theta_{12} \\
\simeq (m_1 + m_2)^2 + p_1p_2 \theta_{12} + (m_1p_2 - m_2p_1)^2/p_1p_2 .
\]

Away from threshold (for example in the charm region) \(\Delta m^2/\delta p \approx m^2/p\) for either opening angle or asymmetry terms dominant, \(\Delta m^2/\delta \theta \approx m^2/\theta^2\) since only the opening angle term contributes. For all momenta assume \(\Delta p/p \approx 0.7\%\); then angle errors are negligible and the error on mass will be \(\Delta m \approx \frac{1}{2} \Delta m \sim \frac{1}{2} \Delta p/p\) from each contributing particle.

The mass resolution can be checked using the abundant strange particle decays, the most frequent being \(K^0 \rightarrow \pi^+\pi^-\) and \(\Lambda^0 \rightarrow p\pi^-\):

\[
\Delta m_{K^0} = \frac{1}{2} m_K \frac{\Delta p}{p} \times \sqrt{2} \times \left( \frac{2 \text{ independent momentum measurements}}{\text{threshold reduction factor}} \right) = 2.0 \text{ MeV/c}^2 .
\]

Similarly \(\Delta m_{\Lambda} = 0.7 \text{ MeV/c}^2\).

When only one branch of a \(V^0\) is reconstructed in the spectrometer, the momentum of the other branch is deduced from transverse-momentum balance. In this case the mass error is increased by \(\sqrt{2}\) since it is not an independent measurement.

The \(K^0, \Lambda^0, \bar{\Lambda}^0\) mass distributions (Figs. 6 and 7) have double the expected widths; the mean values are also slightly too low when both tracks have reconstructed momentum. Both the shift in mass and the increase in expected width can be attributed to the preliminary nature of the magnetic field calibration. To map the field an array of 125 Hall probes was stepped through each magnet in the beam direction, so the field integral along the trajectory of a high energy track was essentially measured by 1 probe/magnet. Beam momentum checks lead to a correction to the field of \(+1.5\%\) for \(M_1\) and \(-1.5\%\) for \(M_2\). It seems reasonable to include an additional contribution to the momentum error on all tracks of \(\Delta p/p = 1.5\%\): this is sufficient to double the expected mass widths. For charmed particle decays the mass
error will then be 10-20 MeV/c² according to decay topology. Figure 8a shows the effective mass of $D^±$ decays into three charged tracks ($K\pi\pi$ or $\pi\pi\pi$) plus 0, 1 or 2 $\pi^0$'s. Each decay contributes four entries, one for each permutation of the kaon; the Cabibbo favoured entries are hatched. The $K^+K^-\pi^0$ combinations are given in Fig. 8b. Four-prong and two-prong $D^0$ decays are shown in Fig. 8c.

6. RECONSTRUCTION EFFICIENCY

About 2% of tracks interact in the exit walls of the bubble chamber or the trigger scintillator; also low-energy tracks may decay before reaching the spectrometer (~5% at 2 GeV/c). Since $V^0$ decays can be identified when only one of the two tracks has its momentum measured, the reconstruction efficiency can be estimated using identified $V^0$'s with both branches expected in the spectrometer. Using pions from identified $K^0$ decays, Fig. 9 shows the momentum distributions for the tracks found in the spectrometer and those expected but not found. Above 2 GeV/c the reconstruction efficiency is 91 ± 3%.
DESIGN PERFORMANCE OF THE NA26 SPECTROMETER

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1. INTRODUCTION

The aim of the NA26 experiment) is to prepare and test the techniques envisaged for the second-generation experiments which study the properties of short-lived particles using a high-resolution bubble chamber.

The experimental set-up consists of the European Hybrid Spectrometer (EHS), shown in Fig. 1, with the new vertex detector placed immediately upstream of the magnet M1.

The performance of the new hydrogen bubble chamber, HOLEBC**), has been described in other talks. The decision to place it outside the field region was taken to avoid building completely new expansion and camera systems, capable of operating in high magnetic field, and because past experience suggests that scanning of short decays in high-multiplicity events is greatly facilitated by having straight tracks. New detectors are planned between the bubble chamber and the first spectrometer wire chamber, with the aim of improving the acceptance for charged tracks in the region of small Feynman x, where most charmed particles are produced, and also of increasing the trigger possibilities. Figure 2 shows an enlarged view of the experimental set-up near the bubble chamber.

In the following I will not describe the expected performance of the EHS, which can be found in the proposals2), but only that of the new detectors. Some preliminary experimental results from the October 1981 test run will also be reported.

2. THE PROPORTIONAL INCLINED CHAMBER (PIC)

This is a proportional wire chamber with drift time read-out3). A chamber of this kind has been used during the last part of the NA16 run4). Two planes with wires at ±10° with respect to the horizontal plane are placed inside M1 for NA26, both to improve the spectrometer acceptance and to make easier the hooking up of tracks reconstructed in the spectrometer with those measured in the bubble chamber. The inclination of the chamber planes is 35° with respect to the vertical.

The principle of operation of PIC is illustrated in Fig. 3. Owing to the inclination of the chamber plane, the tracks cross field-lines corresponding to several wires. A measurement of the drift time therefore gives several measurements of the same tracks. If \( \sigma_T \) is the error on drift time measurement, \( v_D \) the drift velocity, and \( \alpha \) the angle between the track and the field lines, and \( N \) is the number of wires hit, the precision along the chamber plane is given by \( \sigma_x = \sigma_T v_D \frac{\alpha}{\sqrt{N}} \).

The redundancy of information makes possible the internal calibration of the chamber parameters. For tracks at fixed angle (beam), the difference between the drift paths to adjacent wires is given by \( d/\tan \alpha \), d being the wire spacing. Both the drift velocity and the accuracy can then be obtained from the distribution of \( \Delta T \), the time difference between signals on adjacent wires. Figure 4 shows the \( \Delta T \) histogram in clock units, not corrected

*) On leave of absence from INFN-Padova, Italy.
**) Holographic Lexan Bubble Chamber.
for field line distortion near the wires nor for the small differences in the cables' transit time. From Fig. 4 we derive \( v_D \approx 45.4 \, \mu \text{m/ns} \) and \( \sigma_X \approx 85 \, \mu \text{m} \).

The effect of the magnetic field is to change the drift direction of the electrons by the angle \( \theta_B = \tan^{-1} \left( \frac{v_D}{B/E} \right) \), where \( B \) and \( E \) are the magnetic and electric field intensities. With \( B = 1.5 \, \text{T} \) and \( 4.8 \, \text{kV} \) applied, \( \theta_B \approx 8^\circ \). For this reason the measuring accuracy is a function of the magnetic field applied. At 1.5 T, with the polarity chosen in such a way that the angle \( \theta_B \) adds to the inclination of the chamber plane, a value for \( \sigma_X \) lower than 70 \( \mu \text{m} \) has been obtained.

The precision in the position measurement of the tracks is not the only good feature of PIC. It gives also the angle of the track with \( \approx 0.5^\circ \) accuracy on each plane. This will certainly help in the reconstruction of very slow tracks.

A good two-track resolution is also obtained: \( \approx 0.5 \, \text{mm} \). In the presence of two close tracks, the wires above the crossing point collect first the signals from the upper track, the ones below collect those from the lower track. The measured points do not therefore lie on a straight line, but there is sufficient information for measuring both track elements, although with somewhat reduced precision. This possibility is important for disentangling tracks in the very crowded forward cone of fast particles.

3. TRIGGER DETECTORS

The detector SSD1 and chambers W0 and W1 (Fig. 2) are used in the trigger logic: SSD1 is a silicon strip detector with 200 \( \mu \text{m} \) pitch; W0 and W1 are proportional chambers with 0.5 \( \mu \text{m} \) and 1 mm pitch, respectively.

At the fast trigger level, the number of hits in each detector is used to signal an interaction between SSD1 and W0; at the second level, the correlation between the hit positions is used to veto, with high efficiency (\( \approx 70\% \)), interactions occurring in the bubble chamber windows. This represents an increase from 50% to more than 70% in the percentage of useful hydrogen interactions.

I will not go into more details regarding the performance of the trigger system, since this subject will be covered by the talk of S.O. Holmgren.

4. THE MINI DRIFT CHAMBER (MDC)

The MDC is a high-pressure drift chamber capable of reaching very good measurement accuracy (\( \sigma \approx 30 \, \mu \text{m} \)) \(^5\). It consists of several cells (9 in the prototype that has been built) with 10 sense wires each, lying on a plane parallel to the beam direction. The electronics is capable of multihit recording, with a resolving power of \( \approx 1 \, \mu \text{m} \).

The original goal of the MDC was to select off-line events containing secondary decays by searching for tracks that do not point back to the main vertex. The average impact distance of the decay tracks from the main vertex is \( (y) = r \sigma_t \); so, in the case of charged D's, \( (y) \) is of the order of 250 \( \mu \text{m} \), which implies that the measuring precision must be a few tens of microns. This precision can be achieved with the set-up of Fig. 5, using two MDC modules separated by a distance 2\( a \), the first one at \( (d - a) \) from the interaction point. The precision on \( y \) is given by
\[ \sigma_y^2 = \frac{\sigma^2}{2n} \left[ 1 + \frac{1}{\sqrt{2} \gamma^2 \left( \frac{d}{s} \right)^2} \right] = \frac{\sigma^2}{2n} \left( \frac{d}{a} \right)^2, \]

where \( \sigma \) is the measuring precision of the MDC and \( n \) is the number of wires per module.

With \( n = 10 \) and \( s = 5 \text{ cm} \), and with the reasonable assumptions that \( \sigma = 30 \text{ \( \mu \)m} \), \( a = 10 \text{ cm} \), and \( d = 47 \text{ cm} \), we get \( \sigma_y = 32 \text{ \( \mu \)m} \).

The measuring precision is therefore good enough, but it can be spoiled by the multiple scattering contribution to the error, which was neglected in the previous calculation. This amounts to \( \sigma_y^{\text{MS}} = 250/p \text{ (GeV)} \text{ \( \mu \)m} \), much larger than the measuring error, unless for this charm search we use only tracks of high \( (\geq 5 \text{ GeV}) \) momentum.

The charm enrichment is not the only output from the MDCs, although it is the most interesting. They allow a precise location of the main vertex, speeding up the event scanning, particularly if holography is used, and making the track reconstruction in the spectrometer more reliable without bubble chamber measurements.

When employing classical optics with two stereo views, the precise measurement in the direction perpendicular to the film plane will resolve many ambiguities between the matching of tracks in the two views. This in turn could make it possible to have track reconstruction starting from the bubble chamber, in addition to the present procedure which starts from the spectrometer, thus leading to better reconstruction efficiency.

As a last contribution, the MDCs will greatly improve the reconstruction of neutral strange particles decaying outside the bubble chamber -- a very important point if we want to completely reconstruct a large number of charm events.

With a beam momentum of 360 GeV/c, a K\(^0\) produced at rest in the centre of mass will decay into two pions after an average flight of 40 cm (110 cm for a \( \Lambda \)). Therefore in most cases the decay tracks are seen by the spectrometer only after deflection in the not very homogeneous magnetic field of M1; an early precise measurement of these tracks, before they are deflected, could then be essential.

* * *

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5) W. Blum, Design and construction of a High-precision mini drift chamber. Meeting on
   the Miniaturization of High-Energy Physics Detectors, Pisa, 1980, proceedings to be
   published.
Fig. 1 General layout of the European Hybrid Spectrometer. (M1, M2: bending magnets. U2, W1, W2, D1-D6: wire chambers. SAD, ISIS, FC, TRD: particle identification. IGD, FGD: electromagnetic calorimeters. INC, FNC: hadron calorimeters. IH, FH: hodoscopes.)
Fig. 2 Layout of the new detectors around the bubble chamber

Fig. 3 Scheme of one gap of PIC

Fig. 4 Histogram of $\Delta T = |T_{i+1} - T_i|$, the drift time difference for two adjacent wires of PIC.

Fig. 5 Proposed layout for the charm tagging using the MDC
THE OPTICAL FIDUCIAL VOLUME TRIGGER SYSTEM

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The optical fiducial volume trigger system (OFVT) is based on the principle of detecting tracks at the entrance and the exit of the fiducial volume of the Rapid Cycling Bubble Chamber (RCBC). The detection elements are two linear arrays of photosensitive diodes, of 1872 cells each, which are illuminated by a light flash which occurs a few hundred microseconds before the main flash. The fast ESOP processor derives from the diode signals whether or not the interaction took place inside the fiducial volume, thus reducing the cost of film and scanning efforts. More details can be found in the Proceedings of the Second Vézelay Workshop on the EHS High Resolution Vertex Detectors1).

Some very preliminary results were presented, which were not yet available during the EHS Users' Committee Meeting on 4 November 1981. The results are based on a quick scan of 50 pictures only, each taken with an OFVT flash delay of 800 μs. The detection efficiency for beam tracks for this delay was found to be 100%.

The decision logic used is shown in the figure. The local multiplicity increase was examined in a window of ±2 mm with respect to the beam. For the non-interacting beam particles (beam-through criterion) a window of ±1 mm was used. All four wrongly rejected events were elastic two prongs. It is, however, possible to reduce the beam window substantially to improve the results for the elastic and target fragmentation events.

From the figure it follows that the reduction of film cost and scanning efforts might be $70 \pm 15\%$. Of the remaining pictures there are only $7 \pm 7\%$ which do not contain an interaction. The loss of good events (including the elastic ones) is $26 \pm 13\%$. If only the inelastic events are considered this loss is only $7 \pm 7\%$.

At the moment the statistics of this analysis are being increased to obtain more reliable results. The detection efficiency will also be investigated for shorter flash delays down to 500 μs.

* * *

REFERENCE

**OFVT Decision Logic**

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<th>Decisions</th>
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<th>Not OK</th>
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<td>Beam present in first array?</td>
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<td>0</td>
</tr>
<tr>
<td>Local multiplicity increase?</td>
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<td>1</td>
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<tr>
<td>Multiplicity decrease?</td>
<td>Reject event</td>
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<td>1</td>
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<tr>
<td>Large track width?</td>
<td>Accept event</td>
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<td>0</td>
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<tr>
<td>Beam-through criterion?</td>
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<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>44</td>
<td>6</td>
</tr>
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</table>

**Features**

A) Reduction of film = \( \frac{\text{total rejected events}}{\text{total frames}} = \frac{35}{50} = 70 \pm 15\% \)

B) Frames still bad = \( \frac{\text{wrongly accepted events}}{\text{total accepted events}} = \frac{1}{15} = 7 \pm 7\% \)

C) Loss of events = \( \frac{\text{wrongly rejected events}}{\text{good accepted + wrongly rejected events}} \)

- \( \frac{5}{15} = 26 \pm 13\% \) including elastic events
- \( \frac{1}{15} = 7 \pm 7\% \) excluding elastic events
A CLASSICAL STREAMER CHAMBER IN
THE EUROPEAN HYBRID SPECTROMETER

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ABSTRACT
A streamer chamber situated inside the supraconducting spectrometer magnet complements very well a small high-resolution bubble chamber situated a bit further upstream. In the bubble chamber the very short-lived particles will be detected, and in the streamer chamber and the rest of the EHS spectrometer the momenta and identity of the majority of the produced particles will be determined.

1. INTRODUCTION

The European Hybrid Spectrometer (EHS) has been optimized with a relatively large visual detector (RCBC) placed inside the spectrometer magnet M1. For the high-resolution experiments, both planned and in progress, a small bubble chamber of the HOBC and H0LEBC type is placed a few metres upstream of M1. In order not to seriously affect the event reconstruction, track detectors have to be placed between the small bubble chamber and the rest of the existing spectrometer.

A streamer chamber is very well suited for this task. Being a visual detector it has excellent pattern recognition properties, so important when it comes to identify strange particles such as K⁰ and Λ⁰ through their decays. These particles are very frequently produced in the decay of charm particles. The decay of these short-lived particles should be seen in the small bubble chamber.

2. THE STREAMER CHAMBER

The streamer chamber, positioned inside M1, is shown in Fig. 1. The dimensions are limited by the M1 iron structure to a diameter of 1.4 m and a depth of 0.6 m.

The high-voltage pulse, with an amplitude of 600 kV and a duration of about 10 ns, will be generated by Marx power supplies and a Blumlein line. The repetition rate will be 10-15 Hz depending on the running conditions.

The chamber will be operated in the avalanche mode, and consequently the ionization centres will be much smaller than those of streamers. Therefore image intensifiers have to be used. The rather large 90 mm diameter ITT tubes would be well suited for this detector.

The chamber will be filled with a He (30%) + Ne (70%) mixture. More details about the technical aspects of the detector can be found elsewhere[1].

3. EXPECTED STREAMER CHAMBER PERFORMANCES

3.1 Two-track separation

There are several factors that determine the two-track separation [1]: the real avalanche diameter, the optical resolution, and the depth of field.

The relatively high field inside which the detector will be situated, will limit the diffusion of the electrons during the avalanche process, thus reducing the real avalanche
size. It is mainly the rather poor resolution of the film and the image intensifiers that contribute to the expected two-track separation of 0.5-1 mm.

3.2 Momentum accuracy

For low momenta the momentum accuracy is limited by the multiple scattering. For high momenta it is mainly the precision of the position measurement (the so-called setting error) that dominates the uncertainty in the momentum determination. For a 3.5% radiation length and a 100 μm setting error in space, the momentum accuracy shown in Fig. 2 is obtained for an integrated field of 2 T m. The Δp/p is smaller than 1% up to a momentum of about 30 GeV/c.

3.3 Particle identification

The primary ionization can be estimated just by counting the avalanches. Assuming the number of detected avalanches to be around 400, it will be possible to obtain a FWHM of the ionization determination of 11%. Figure 3 shows the expected particle separation as a function of the momentum. The particle identification will be particularly useful in the momentum range 3-80 GeV/c.

4. THE TRIGGER

One of the advantages with the streamer chamber is its triggering ability. The minimum time between the occurrence of an event and the application of the high-voltage pulse is around 1 μs. This delay should be kept small to reduce the effect of electron diffusion and the background due to late incoming particles. This latter effect can be reduced by applying the beam kicker at an early stage. The optimal running conditions might very well be different for different experiments.

With a more restrictive event selection there will be fewer pictures to inspect; but for these one would, on the other hand, like to have the most complete information possible.

5. SUMMARY

A streamer chamber in MI will have:

- good pattern recognition capacity;
- excellent momentum determination;
- good two-track separation;
- good particle identification, in particular the identification of neutral strange particles via their decays.

The combination of a small high-resolution (holographic) bubble chamber and a streamer chamber filling the MI magnet seems to be a very efficient one.

* * *

REFERENCE

Fig. 1 The streamer chamber placed inside the M1 iron structure

Fig. 2 The error in the momentum determination for an integrated field of 2 Tm

Fig. 3 The particle separation as a function of momentum for 1.4 m tracks in a He-Ne gas mixture giving about 400 avalanches; $\Delta n_p$ is the difference in number of avalanches and $\sigma$ is the standard deviation.
DATARATES AND TRIGGERING

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University of Stockholm

ABSTRACT

Some numbers and thoughts concerning the event rates and triggering for charm experiments in EHS have been collected in this note.

1. EVENTRATES

1.1 Constraints on event rates

The drift chambers impose a limit on the number of charged particles per SPS spill. This is due to the space charge effect and the fact that transverse dimensions of the beam are very small; 2x30 mm at the centre of HOLEBC. With the present set up one empirically limits the flux to \( <5 \times 10^4 \) beam particles per spill. With the introduction of a rotating collimator, expected for spring '82, this can probably be increased. ISIS can handle the present rate thanks to 'gain switching' in between BC sensitive periods.

For comparisons we choose charge beam intensities limited to \( 8 \times 10^4 \) particles per spill.

Other constraints come from the vertex detector repetition rate and sensitive times and the camera system repetition rate. For certain beams the beam itself imposes rate limitations. Below we summarize the present state of art.

<table>
<thead>
<tr>
<th>Presently Achievable Range</th>
<th>Our Choice for Comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift chambers and ISIS</td>
<td>( &lt; 4 \times 10^4 ) /spill</td>
</tr>
<tr>
<td>BC sensitive time</td>
<td>( &lt; 600 ) microsec</td>
</tr>
<tr>
<td>BC expansion rate</td>
<td>30 - 50 Hz</td>
</tr>
<tr>
<td>Camera rate</td>
<td>10 - 20 Hz</td>
</tr>
<tr>
<td>SPS cycle</td>
<td>72000 2sec spill per 24 hours</td>
</tr>
<tr>
<td>K enriched beam</td>
<td>( &gt; 7% ) K</td>
</tr>
<tr>
<td>Photon beam</td>
<td>( &lt; 1 ) Mpart/spill (&gt;50 GeV)</td>
</tr>
</tbody>
</table>


These are realistic numbers for a run for instance in spring 1982. It is certainly possible to improve several of these numbers but one should not expect dramatic improvements in very the near future.

1.2 Event rates for different beams  
-----------------------------------

With the numbers given above one can attempt to make a comparison of event rates for different beam particles. For this comparison we will assume that the usable length of H in HOLEBC is 10 cm. In Table 1 we compare cross sections and event rates per beam for different beam particles.

<table>
<thead>
<tr>
<th>beam</th>
<th>Z(tot) [mb]</th>
<th>Z(trigg) [mb]</th>
<th>L(trigg) [cm]</th>
<th>#events/beam [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>pi-</td>
<td>25</td>
<td>15</td>
<td>1775</td>
<td>0.56</td>
</tr>
<tr>
<td>K+</td>
<td>20</td>
<td>10</td>
<td>2664</td>
<td>2.7x10^2</td>
</tr>
<tr>
<td>p or p</td>
<td>40</td>
<td>30</td>
<td>888</td>
<td>1.13</td>
</tr>
<tr>
<td>photon</td>
<td>0.1</td>
<td></td>
<td>2.7x10^5</td>
<td>3.8x10^-3</td>
</tr>
</tbody>
</table>

a) \[ Z(\text{trigg}) = Z(\text{tot}) - (Z(\pi) + Z(p) + ...) \]
b) \[ Z(\text{tot}) = 10 \text{ mb} \]

From these numbers one can obtain average number of events per SPS spill. In doing this one has to correct, downwards, for camera dead times and for the chance of having more than one interactions per expansion. In case of a small hydrogen BC, like HOLEBC or LEBEC, the beam windows contribute background events at about the same rate as the hydrogen inside the fiducial volume. The presence of the background events will increase these corrections if the trigger cannot distinguish between events inside and outside the fiducial volume. In fact an 'electronic fiducial volume trigger' (EFVT), designed to do just that, will be described later.

In Table 2 we compare cross section sensitivities we give two numbers in most cases; one without fiducial volume trigger and one were we assume that the EFVT will veto 70% of the background events. Moreover in
order to get some realistic estimates for an experiment we assume 50% overall efficiency in the datataking. This is meant to cover intermittent break downs of SPS and major spectrometer components which empirically always occur at about this rate.

<table>
<thead>
<tr>
<th>beam</th>
<th>no FVT</th>
<th>EFVT</th>
<th>no FVT</th>
<th>EFVT</th>
<th>no FVT</th>
<th>EFVT</th>
<th>produced</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EFVT</td>
</tr>
<tr>
<td>pi-</td>
<td>10.4</td>
<td>8.2</td>
<td>12.5</td>
<td>15</td>
<td>374k</td>
<td>295k</td>
<td>375</td>
</tr>
<tr>
<td>K+</td>
<td>0.86</td>
<td>0.56</td>
<td>1.5</td>
<td>1.5</td>
<td>31k</td>
<td>20k</td>
<td>38</td>
</tr>
<tr>
<td>p or ā</td>
<td>14.8</td>
<td>12.1</td>
<td>8.9</td>
<td>11.1</td>
<td>533k</td>
<td>435k</td>
<td>278</td>
</tr>
<tr>
<td>photon</td>
<td>1.5</td>
<td>0.98</td>
<td>270</td>
<td>270</td>
<td>108k</td>
<td>70k</td>
<td>270</td>
</tr>
</tbody>
</table>

a) EFVT is assumed to veto 70% of events in BC windows
b) Z(\text{charm}) = 25\text{micb} for hadrons, 1\text{micb} for photon beam is assumed

In Table 2 we also give an estimate of the number of charm events produced in the different cases based on very crude assumptions for the corresponding production cross sections.

As can be seen from the numbers in Table 2 the fiducial volume trigger will increase the sensitivity of the experiment by ~20% and ~25% for pion or proton beam respectively. In addition one has to use 50% more film to arrive at a given sensitivity if one has no EFVT.

Concerning the number of produced charm events, pion, proton or photon beams seem to give about the same yield per unit of running time. The relative differences are certainly within the errors of our cross section estimates. For the case of a K+ beam the charm yield is however down by about an order of magnitude due to the nature of the beam. The only way to overcome this would be to increase the beam intensity by a corresponding amount. This in turn would imply a similar improvement of the rate capability in the BC (holography) and in the spectrometer (cure spacecharge effects in the beam region).

For the case of photon beam we have assumed that the amount of accom-
panying electron background from pairs and comtons is compatible with the charge particle rate capabilities at the assumed beam intensity. This can probably be verified only empirically. In addition this experiment will most probably require holographic read out of the BC in order to cope with the geometrical beam profile.

2. TRIGGERING
-------

2.1 Trigger Structure

The trigger has several functions which can be summarized as follows

i) strobing or gating all spectrometer components including the flash and kicker magnet;

ii) selecting different event types e. g.

- beam through
- wide beam for survey
- interactions

iii) selecting physically interesting events if possible

Based on timing properties the trigger is usually organized in trigger levels. In general one tries to put any given condition at the lowest possible level in order to save unnecessary dead times. The present EHS trigger is organized in the following way:

<table>
<thead>
<tr>
<th>level</th>
<th>purpose</th>
<th>implementation</th>
<th>timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>to give fast strobos to trigger detectors</td>
<td>coincidence between beam scintillators</td>
<td>≤ 70 ns</td>
</tr>
<tr>
<td>1</td>
<td>interaction trigger or beam through to strobe spectrometer detectors (WC's, DC's...)</td>
<td>scintillators (NA23) MWPC's + SSD's (NA26)</td>
<td>≤ 200 ns</td>
</tr>
<tr>
<td>2</td>
<td>refined interaction trigger e.g. tagging</td>
<td>CEDAR's and fast clears</td>
<td>≤ 700 ns</td>
</tr>
<tr>
<td>3</td>
<td>veto BC picture and spectrometer read out for background events</td>
<td>OFVT (RCBC) EFVT (HOLEBC)</td>
<td>~ 10 mysec ~ 300 mysec</td>
</tr>
</tbody>
</table>

2.2 An Example
-------

As an illustration we can take the NA26 trigger. Fig 1 shows a sketch of the layout and some characteristics of the different detectors used.
The 0-level trigger is formed by the following coincidence condition for the beam scintillators:

\[ \text{beam strobe} = T1 \times T2 \times T3 \times T4 \times (V1+V2) \]

which ensures a beam particle without companions and in the focal plane of the cameras. Figs 2-3 show the beam profiles and cluster sizes obtained in SSD1, W0 and W1 for this trigger.

The 1-level trigger selects a multiplicity of one in SSD1 and a range of multiplicities in W0 and W1. Fig 4 shows the logic layout for this trigger. Fig 5-6 show results from this trigger obtained from a testrun in Nov. 1981. With the multiplicity requirement >2 in both W0 and W1 we measured an interaction rate of 2.7%, with chamber (HOLEBC) full and 1.3%, with chamber empty in a proton beam (200GeV). This gives an interaction rate of 1.4% which is in excellent agreement with Table 1 considering that the total H length is 12cm in HOLEBC.

The 3-level trigger is an 'electronic fiducial volume' trigger, EFVT. The principle of the trigger is illustrated in Fig 7. The idea is to look up extreme hits in W0, predict the corresponding hit regions in W1 assuming the interaction to be placed in either of the beam windows. When predictions match real hits in W1 the event is considered to be a window event and vetoed. Simulations indicate about 70% veto efficiency and about 5% loss of useful events. Some data were taken in the testrun mentioned above but the off-line analysis is not yet advanced enough to be compared with the simulation results.

There is also within NA26 active work going on on a charm trigger. The trigger is based on a set of small high precision high pressure drift chambers modules placed very close to HOLEBC. This trigger however is not foreseen in the on-line logic but rather as an off-line trigger to select frames for scanning. For details we refer to the NA26 proposal and internal reports (Zumerle...).

2.3 Physics Trigger

Charm events occur in \(< \sim 1/1000\) of all reactions for hadronic beams.
For EHS (NA16 and NA27) the physics trigger so far is 'the scanning of events in the BC-picture'. This trigger has the great and often underestimated advantage of being a 'minimum bias' trigger. However, if high statistics (few \( \times 10^3 \)) is sought this trigger soon becomes unmanageable.

An on-line trigger can be added in the trigger system at the latest in the 3-level i.e. it has to be faster than 5-10 msec otherwise it has to be off-line.

In a sense a photon beam experiment is a solution since the relative charm event rate over is better by about an order of magnitude when compared to hadronic beams. However, as can be seen in Table 3 the yield per unit of running time is similar the one obtained in the present hadronic beam experiments.

With a hadronic beam one could easily increase the beam intensity and hence the yield if a selective on-line trigger could be found. This of course implies holographic BC recording and fixes in the spectrometer in order to cope with these higher rates.

3. CONCLUSIONS

For a 'minimum bias' triggered charm experiment with pion or proton beams in EHS and with a small BC (e.g. HOLEBC) the data rates and analysing power seem to be well matched. Such experiments (NA16,NA27) will produce samples of a few hundred reconstructed events.

An electronic fiducial volume trigger for this case is being developed. In addition a candidate for an off-line trigger for charm based on high precision drift chambers is being pursued.

For the next step, i.e. a few thousand charm events and some with beauty, one has to do either or, hopefully, both of two things:

i) increase the running time by an order of magnitude and use a high energy photon beam together with holographic BC read out.

ii) Find an on-line charm trigger for the use with a high intensity hadron beam and holographic BC read out.
NA 26 TRIGGER

T1/T2  T4  T3  V1, 2

Detectors:

<table>
<thead>
<tr>
<th>Detector</th>
<th>Pitch</th>
<th>Strips/Wires</th>
<th>yxz [cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSD1</td>
<td>0.2 mm</td>
<td>100 strips</td>
<td>3 x 2</td>
</tr>
<tr>
<td>W0</td>
<td>0.5 mm</td>
<td>160 wires</td>
<td>8 x 8</td>
</tr>
<tr>
<td>W1</td>
<td>1 mm</td>
<td>320 wires</td>
<td>32 x 32</td>
</tr>
<tr>
<td>T3</td>
<td></td>
<td></td>
<td>10 x 0.2</td>
</tr>
<tr>
<td>T4</td>
<td>Scintillators</td>
<td></td>
<td>4 x 10</td>
</tr>
</tbody>
</table>

T1/T2

0-level trigger:

Beam strobe = \( T1 \cdot T2 \cdot T3 \cdot T4 \cdot (V1+V2) \)

Fig. 1 Layout of NA26 trigger
Fig. 2 Wiremaps for beam trigger. a) SSD1, b) W0, c) W1.
Fig. 3 Clustersizes for beam trigger. a) SSD1, b) W0, c) W1.
y = X2 \cdot \overline{X3} \cdot X4 \cdot X6

Fig. 4 Logic of the interaction trigger

![Diagram](image)

Fig. 5 Number of wires hit for interaction trigger events i.e. discr. level set to 100 mV.  
a) W0, b) W1.
Fig. 6 Wiremaps for interaction trigger events. a) W0, b) W1.

Fig. 7 Principles of the 'electronic fiducial volume trigger', EFVT
BEAM POSSIBILITIES FOR THE EUROPEAN HYBRID SPECTROMETER

P. Coet, N. Doble and S. Reucroft
CERN, Geneva, Switzerland.

ABSTRACT
The basic characteristics of the SPS H2 beam serving the European Hybrid Spectrometer (EHS) are presented, including brief descriptions of the target station capabilities, the various optical modes and instrumentation of the beam as well as the particle fluxes available, as measured in experiment NA20. Special facilities which have been introduced or are planned for EHS are: time-modulation, enriched (K$^+$), and tertiary (p, e) beams, including a proposed $\gamma$-tagging system. Finally some remarks on possible future developments (e.g. extracted $\bar{p}$ and neutral beams) are made with a view to widening the discussion.

1. BEAM LAYOUT AND INSTRUMENTATION

The H2 beam is a high-energy, high-resolution, secondary beam which was designed as a general facility in the North Experimental Area of the Super Proton Synchrotron (SPS)\textsuperscript{1).

Like the other beams feeding the hall E11 with secondary particles, the principal deflections of the beam line are situated in the vertical plane, introducing a difference in altitude of 8.44 m between the targeting area and the experimental floor. This layout was adopted to provide adequate earth shielding covering the target area, and to bury the main muon flux below the experimental hall, thereby allowing the positioning of experiments in the hall without reference to the targeting of the primary beam.

Only moderate bending is introduced in the horizontal plane to provide adequate lateral separation from the neighbouring H4 beam.

The basic layout of the H2 beam is represented in Fig. 1. It comprises at least four optical stages.

The first vertical bend is used for momentum analysis and the second for dispersion recombination. The second bend serves also as central part of a spectrometer section for accurate momentum measurement\textsuperscript{1).}

The fourth stage includes a section where the beam is made parallel in both planes. Two Čerenkov Differential counters with Achromatic Ring focus (CEDAR)\textsuperscript{3) are installed in this section and offer the possibility to identify and flag particles according to their mass.

Following the focusing of the beam to an experimental position $\sim 70$ m upstream of EHS, a final stage can be used to match the beam to the conditions required for EHS. At present this stage comprises a single quadrupole, located $\sim 30$ m away, used to focus the beam to a horizontal spot of $\sim 1$ mm width near the bubble chamber vertex detector, whilst allowing the beam to diverge in the vertical plane. This configuration can be supplemented by further quadrupoles, if either smaller horizontal spot sizes or a vertically parallel beam are required.

Alternatively, the beam line is capable of transporting primary protons of maximum momentum, but this facility is restricted to use at reduced intensity.

The principal parameters of the beam are given in Table 1.
Table 1

H2 beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum momentum</td>
<td>400 GeV/c (450 GeV/c for primary protons)</td>
</tr>
<tr>
<td>Acceptance</td>
<td>1.5 μsr (2.5 μsr at p ≤ 200 GeV/c)</td>
</tr>
<tr>
<td>Δp/p maximum</td>
<td>±2.0%</td>
</tr>
<tr>
<td>Production angle</td>
<td>0° possible for -400 &lt; p &lt; +130 GeV/c together with beam H4</td>
</tr>
<tr>
<td>Dispersion at momentum slit</td>
<td>28 mm/°Δp/p</td>
</tr>
<tr>
<td>Intrinsic Δp/p with slit closed</td>
<td>±0.05%</td>
</tr>
<tr>
<td>Length of beam to EHS (RCBC)</td>
<td>601.6 m</td>
</tr>
<tr>
<td>Beam height in EHN1</td>
<td>2.46 m</td>
</tr>
</tbody>
</table>

2. GENERAL CHARACTERISTICS

2.1 Target station

Two high-energy beams, H2 and H4, are derived from the same target T2. The target station, shown schematically in Fig. 2, incorporates a set of three magnets allowing the primary proton beam to be 'wobbled' by an angle which may be varied to change the relation between the momenta of the two beams.

This scheme allows a variety of possible combinations of primary protons, secondary hadrons, and tertiary electrons over wide ranges of momenta to be available to the two beams, as indicated in Fig. 3.

When both beams require secondary hadrons, the choice of their momenta is subject to some degree of coupling, which depends on the production angle permitted. This is illustrated in Fig. 4.

All combinations of momenta are possible when the two beams have opposite polarity and when production angles different from zero are acceptable for one or other of the beams. Operational conditions are more restrictive when both beams are working with the same polarity.

When electrons are used in the H4 beam, hadrons of either sign and all momenta higher than ~ 100 GeV/c are possible for H2.

2.2 Optical modes

The H2 beam can be operated in three different optical modes simply by changing the configuration of quadrupole currents. These are referred to as:

i) high-resolution mode,
ii) high-transmission mode,
iii) filter mode (see Fig. 7).

Quadrupoles acting as field lenses, and a sextupole for correction of chromatic aberration in the horizontal plane, are available in the momentum analysis section of the beam and are used in the different optical modes to achieve the best performance.
The choice of optical mode is determined by experimental requirements with regard to beam quality and flux. The best beam definition is obtained with the high-resolution mode at the price of lower intensity relative to the two other modes.

Two different arrangements of the three front-end quadrupoles are also possible, giving a higher acceptance for momenta up to 200 GeV/c.

The characteristics of the beam are given in Table 2 for the different modes and front-end quadrupole arrangements.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Front end</th>
<th>Maximum momentum (GeV/c)</th>
<th>Δp/p (%)</th>
<th>Acceptance</th>
<th>Sextupole correction of chromatic aberration</th>
</tr>
</thead>
<tbody>
<tr>
<td>High resolution</td>
<td>FDF</td>
<td>200</td>
<td>0.8</td>
<td>0.7</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>FFD</td>
<td>400</td>
<td></td>
<td>0.4</td>
<td>2.4</td>
</tr>
<tr>
<td>High transmission</td>
<td>FDF</td>
<td>200</td>
<td>2.0</td>
<td>0.7</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>FFD</td>
<td>400</td>
<td></td>
<td>0.4</td>
<td>6.0</td>
</tr>
<tr>
<td>Filter</td>
<td>FDF</td>
<td>200</td>
<td>2.0</td>
<td>0.7</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>FFD</td>
<td>400</td>
<td></td>
<td>0.4</td>
<td>6.0</td>
</tr>
</tbody>
</table>

2.3 Hadron fluxes
Extensive measurements have been carried out with the H2 beam to determine the absolute production rate and composition of secondaries from proton-beryllium collisions at 400 GeV/c.

The measurements were made on positive and negative particles for different momenta, transverse momenta, and target lengths.

The maximum total particle fluxes which can be transported by the beam are represented in Fig. 5 at zero production angle for a 500 mm Be target.

The beam composition at production is given in Table 3 for all the experimental conditions investigated.

3. SPECIAL FACILITIES FOR EHS
3.1 Time modulation of the beam
Only a slow extracted primary proton beam is provided from the SPS towards the North Experimental Area, giving uniform spills of typically 1-2 s duration at repetition times of 10-15 s.

The use of rapid cycling bubble chambers (RCBCs) in beam H2 has led to the installation of a pulsed magnet system to modulate the beam spill in the primary beam branch feeding target T2 with protons.

The system employs a fast kicker which deflects the beam vertically downwards, removing the proton spill from the target and thereby interrupting the production of secondaries for a number of short intervals during the spill.
### Table 3

Particle contents, in percent, of the beam leaving the beryllium production target as measured by NA20[^1] with 400 GeV/c protons

<table>
<thead>
<tr>
<th>P (GeV/c)</th>
<th>PT (MeV/c)</th>
<th>Target length (mm)</th>
<th>e^-</th>
<th>e^+</th>
<th>p</th>
<th>K^-</th>
<th>K^+</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0</td>
<td>100</td>
<td>11.2 ± 0.3</td>
<td>79.3 ± 1.0</td>
<td>6.4 ± 0.2</td>
<td>3.1 ± 0.2</td>
<td>7.1 ± 0.2</td>
<td>69.7 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>22.0 ± 0.7</td>
<td>69.2 ± 1.0</td>
<td>6.2 ± 0.2</td>
<td>2.5 ± 0.1</td>
<td>14.4 ± 0.4</td>
<td>63.3 ± 0.7</td>
<td>6.93 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>28.2 ± 0.8</td>
<td>64.2 ± 1.2</td>
<td>5.5 ± 0.2</td>
<td>2.1 ± 0.1</td>
<td>19.2 ± 0.6</td>
<td>58.9 ± 0.8</td>
<td>6.69 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>1.83 ± 0.05</td>
<td>84.9 ± 0.8</td>
<td>8.71 ± 0.11</td>
<td>4.63 ± 0.08</td>
<td>0.99 ± 0.07</td>
<td>67.8 ± 0.9</td>
<td>9.5 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>3.57 ± 0.11</td>
<td>83.4 ± 0.8</td>
<td>8.84 ± 0.11</td>
<td>4.23 ± 0.07</td>
<td>1.91 ± 0.13</td>
<td>65.6 ± 0.9</td>
<td>9.8 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>4.63 ± 0.14</td>
<td>82.5 ± 0.8</td>
<td>9.06 ± 0.12</td>
<td>3.83 ± 0.07</td>
<td>2.33 ± 0.16</td>
<td>64.6 ± 0.8</td>
<td>9.7 ± 0.2</td>
</tr>
<tr>
<td>120</td>
<td>0</td>
<td>2.8 ± 0.7</td>
<td>89.5 ± 1.1</td>
<td>5.87 ± 0.07</td>
<td>1.86 ± 0.03</td>
<td>1.1 ± 0.2</td>
<td>57.6 ± 0.7</td>
<td>4.55 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>8.0 ± 0.8</td>
<td>84.6 ± 1.1</td>
<td>5.79 ± 0.07</td>
<td>1.64 ± 0.02</td>
<td>2.8 ± 0.6</td>
<td>55.9 ± 0.9</td>
<td>4.69 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>9.1 ± 0.9</td>
<td>83.5 ± 1.2</td>
<td>5.87 ± 0.07</td>
<td>1.49 ± 0.02</td>
<td>3.9 ± 0.8</td>
<td>54.5 ± 1.1</td>
<td>4.80 ± 0.06</td>
</tr>
<tr>
<td>300</td>
<td>0</td>
<td>1.7 ± 0.3</td>
<td>89.4 ± 0.7</td>
<td>6.81 ± 0.08</td>
<td>2.16 ± 0.03</td>
<td>0.5 ± 0.1</td>
<td>49.1 ± 0.6</td>
<td>5.80 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>4.3 ± 0.9</td>
<td>86.8 ± 1.0</td>
<td>6.90 ± 0.08</td>
<td>1.95 ± 0.03</td>
<td>1.3 ± 0.3</td>
<td>48.3 ± 0.6</td>
<td>5.82 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>5.2 ± 1.0</td>
<td>86.2 ± 1.2</td>
<td>6.92 ± 0.08</td>
<td>1.76 ± 0.03</td>
<td>1.6 ± 0.3</td>
<td>47.9 ± 0.7</td>
<td>6.05 ± 0.07</td>
</tr>
<tr>
<td>500</td>
<td>0</td>
<td>1.1 ± 0.2</td>
<td>89.2 ± 0.3</td>
<td>7.13 ± 0.09</td>
<td>2.58 ± 0.04</td>
<td>0.3 ± 0.1</td>
<td>43.6 ± 0.5</td>
<td>6.69 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>2.6 ± 0.5</td>
<td>87.8 ± 0.8</td>
<td>7.23 ± 0.09</td>
<td>2.35 ± 0.04</td>
<td>0.7 ± 0.2</td>
<td>43.0 ± 0.5</td>
<td>6.78 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>3.7 ± 0.7</td>
<td>86.7 ± 1.0</td>
<td>7.40 ± 0.09</td>
<td>2.13 ± 0.03</td>
<td>1.1 ± 0.2</td>
<td>42.8 ± 0.5</td>
<td>7.02 ± 0.08</td>
</tr>
<tr>
<td>200</td>
<td>0</td>
<td>(a)</td>
<td>95.0 ± 0.6</td>
<td>4.30 ± 0.13</td>
<td>0.66 ± 0.03</td>
<td>(a)</td>
<td>21.0 ± 0.6</td>
<td>2.49 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>(a)</td>
<td>95.0 ± 0.6</td>
<td>4.33 ± 0.13</td>
<td>0.60 ± 0.02</td>
<td>(a)</td>
<td>20.8 ± 0.6</td>
<td>2.55 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>(a)</td>
<td>95.0 ± 0.6</td>
<td>4.44 ± 0.13</td>
<td>0.55 ± 0.02</td>
<td>(a)</td>
<td>21.8 ± 0.7</td>
<td>2.78 ± 0.11</td>
</tr>
<tr>
<td>500</td>
<td>0</td>
<td>94.2 ± 0.6</td>
<td>5.05 ± 0.20</td>
<td>0.76 ± 0.03</td>
<td>16.4 ± 0.5</td>
<td>3.12 ± 0.09</td>
<td>80.4 ± 1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>94.1 ± 0.6</td>
<td>5.21 ± 0.21</td>
<td>0.69 ± 0.03</td>
<td>17.1 ± 0.5</td>
<td>3.28 ± 0.10</td>
<td>79.6 ± 1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>94.3 ± 0.6</td>
<td>5.15 ± 0.21</td>
<td>0.60 ± 0.02</td>
<td>17.5 ± 0.5</td>
<td>3.44 ± 0.10</td>
<td>79.9 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>0</td>
<td>98.9 ± 0.4</td>
<td>1.04 ± 0.02</td>
<td>0.047±0.002</td>
<td>(a)</td>
<td>(b)</td>
<td>2.03 ± 0.04</td>
<td>0.617±0.012</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>98.9 ± 0.4</td>
<td>1.10 ± 0.02</td>
<td>0.046±0.002</td>
<td>(a)</td>
<td>(b)</td>
<td>2.09 ± 0.04</td>
<td>0.638±0.019</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>98.8 ± 0.4</td>
<td>1.13 ± 0.02</td>
<td>0.042±0.002</td>
<td>(a)</td>
<td>(b)</td>
<td>2.01 ± 0.04</td>
<td>0.641±0.012</td>
</tr>
</tbody>
</table>

**Note:**

- a) For P ≥ 200 GeV/c the e^±'s produced in the target are lost before the CEDARS owing to synchrotron radiation in the bending magnets.
- b) 300 GeV/c, PT = 0 positives were not measured.
The operating mode of the kicker can be chosen so as to produce two pulses separated by a variable delay, thus providing a window covering the required sensitive time of the bubble chamber at an adjustable repetition rate.

The main characteristics of the upgraded pulsed magnet system are:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of first pulse</td>
<td>(\sim 1.5) ms</td>
</tr>
<tr>
<td>Duration of second pulse</td>
<td>(\sim 2.5) ms</td>
</tr>
<tr>
<td>Variable delay between pulses</td>
<td>0-2 ms</td>
</tr>
<tr>
<td>Fall time of first pulse and rise</td>
<td>(\sim 20) (\mu s)</td>
</tr>
<tr>
<td>time of second pulse</td>
<td></td>
</tr>
<tr>
<td>Maximum repetition rate</td>
<td>(\sim 50) Hz</td>
</tr>
</tbody>
</table>

The presence of a continuous flux of secondaries in the H2 beam between successive expansions of the bubble chamber is useless and may limit the instantaneous useful particle rate owing to saturation of the EHS drift chambers.

A project is being realized to suppress the continuous spill of particles (except muons) between expansions by means of a mechanical shutter placed in the beam.

This will consist of a rotating collimator in the form of a steel cylinder 80 cm long and 16 cm in diameter. Two beam slots of 50 \(\times\) 12 mm\(^2\) will be provided symmetrically along a diameter, as shown in Fig. 6a.

The rotating collimator will be installed downstream of the second vertical bend at a position where the beam, used in the filter mode, has a double focus (Fig. 7). Its speed of rotation will be adjustable so as to provide bursts at a repetition rate between 2 and 60 Hz, with a constancy of 0.5%, to which the bubble chamber expansions must then be synchronized. By displacing the collimator laterally with respect to the beam, it will be possible to adjust the pulse length from 5% to 15% of the repetition time.

Combining the effect of the fast kicker magnet and of the rotating collimator, it can be arranged that particles reach the experiment virtually only during the sensitive time of the bubble chamber, as demonstrated qualitatively in Fig. 6b.

3.2 Enriched secondary \(K^+\) beam

The optics of the beam in the filter mode, shown in Fig. 7, provides a double focus at the position of the first field lens.

A filter installed near this point gives the possibility of enriching the beam in positive kaons, whilst preserving the optical properties of the beam.

The technique uses the preferential absorption of protons and pions in matter\(^4\).

Preliminary calculations\(^7\), taking into account beam production angle and filtering material, have suggested a production angle of 2-4 mrad and a filter of polyethylene (C\(_2\)H\(_4\)) some 5 m long as providing close to optimum conditions. This has been estimated to attenuate the \(K^+\) in the beam by a factor of \(\sim 50\) whilst attenuating \(\pi^+\) by \(\sim 100\) and protons by \(\sim 500\).

A filter, 5.5 m long, has been installed and can be introduced into the beam in steps of 0.5 m.

In choosing the filter length and hence the attenuation factors, some additional conditions must be considered:
i) The pions decaying before the filter create muons which are, to some extent, transported and produce a background, at the end of the beam, which is proportional to the flux incident on the filter. This background therefore increases with filter length relative to the final beam flux.

ii) The beam divergence at the CEDAR counters and hence the efficiency with which the K\(^+\) can be tagged, must also be taken into account, since multiple and elastic nuclear scattering in the filter tend to increase the beam emittance.

To study these problems, a series of measurements has been started at +250 GeV/c and +220 GeV/c for different filter lengths and production angles.

The results, not yet complete, are summarized in Table 4 and a representative CEDAR pressure scan is shown in Fig. 8.

For the natural, unfiltered beam, only the content at 250 GeV/c, 2.12 mrad production angle, has been measured during these studies; the other values are extrapolated from particle production measurements\(^1\).

Only lower limits have been obtained for the muon background counted in the beam, leading to corresponding lower limits for the efficiency with which the CEDAR could detect the hadrons.

**Table 4**

<table>
<thead>
<tr>
<th>Beam</th>
<th>+250 GeV/c 2.12 mrad</th>
<th>+250 GeV/c 4 mrad</th>
<th>+220 GeV/c 1.61 mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter length</td>
<td>Natural</td>
<td>3 m</td>
<td>5 m</td>
</tr>
<tr>
<td>Total flux attenuation</td>
<td>1</td>
<td>~3 × 10(^{-2})</td>
<td>~2 × 10(^{-3})</td>
</tr>
<tr>
<td>Hadron content</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% protons</td>
<td>91.7</td>
<td>72</td>
<td>52</td>
</tr>
<tr>
<td>% kaons</td>
<td>1.2</td>
<td>6</td>
<td>12.3</td>
</tr>
<tr>
<td>% pions</td>
<td>7.1</td>
<td>22</td>
<td>35.6</td>
</tr>
<tr>
<td>CEDAR efficiency (% of total flux)</td>
<td>86</td>
<td>30</td>
<td>48</td>
</tr>
<tr>
<td>(\mu) background (% of total flux)</td>
<td>-</td>
<td>-</td>
<td>(\zeta) 17</td>
</tr>
<tr>
<td>Corrected CEDAR efficiency (% of hadrons) ((\mu) background subtracted)</td>
<td>-</td>
<td>-</td>
<td>(\zeta) 60</td>
</tr>
</tbody>
</table>

3.3 Tertiary antiproton beam from \(\bar{\Lambda}\) decay

The natural content of antiprotons produced by interaction of 400 GeV/c protons varies from about 2% at 100 GeV/c to about 0.5% at 200 GeV/c \(^4\).

This percentage can be improved by using the decay of the \(\bar{\Lambda}\) created at the target to produce the \(\bar{\rho}\).

Using the same target station setting as for electron production (see Section 3.4), the charged particles are first swept away, leaving a free drift space of 16 m for the \(\bar{\Lambda}\) decay
process. The $\pi^-$ content in the beam then comes from $K^0_S$ decay and, at low energy, additionally from $\Lambda$ decay.

This process has not yet been checked experimentally in the H2 beam although no modifications to the layout are required. However, calculations have been made\textsuperscript{7) which are consistent with the experimental results obtained by Neale at FNAL\textsuperscript{8).}

In these calculations, the $\bar{\Lambda}$ were assumed to be produced in momentum and angle in the same way as $\bar{p}$, but with half the total cross-section as indicated by experiment and theory. The $\bar{p}$ and $\pi^-$ [from $K^0_S = \frac{1}{2}(K^0 + \bar{K}^0) = \frac{1}{2}(K^+ + K^-)$] at production are projected back to the target position to give the apparent radial target size for the beam. Table 5 summarizes the fluxes and ratios for various radial selections, which may be transported by the H2 beam.

It appears that with suitable collimation, the $\bar{p}$ content of the beam may be raised to $\sim 30\%$ at 100 GeV/c falling to $\sim 10\%$ at 150 GeV/c. At lower momenta the dominant contamination is expected to be $\pi^-$ from $\Lambda$ decay, though a more recent measurement at FNAL\textsuperscript{9) indicates the possibility of achieving $30\%$ $\bar{p}$ content in a beam at 50 GeV/c derived from 400 GeV/c primary protons at 6 mrad production angle.

<table>
<thead>
<tr>
<th>Momentum (GeV/c)</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total $\bar{p}$</td>
<td>$4.41 \times 10^7$</td>
<td>$1.75 \times 10^7$</td>
<td>$3.76 \times 10^7$</td>
<td>$3.30 \times 10^7$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>$5.33 \times 10^6$</td>
<td>$4.09 \times 10^6$</td>
<td>$2.19 \times 10^6$</td>
<td>$7.01 \times 10^6$</td>
</tr>
<tr>
<td>Ratio $\bar{p}/\text{total}$</td>
<td>0.07</td>
<td>0.04</td>
<td>0.017</td>
<td>0.005</td>
</tr>
<tr>
<td>Flux inside $r \leq 10$ mm at target $\bar{p}$</td>
<td>$1.83 \times 10^7$</td>
<td>$1.46 \times 10^7$</td>
<td>$3.75 \times 10^7$</td>
<td>$5.30 \times 10^7$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>$3.51 \times 10^6$</td>
<td>$9.45 \times 10^6$</td>
<td>$1.21 \times 10^6$</td>
<td>$6.71 \times 10^6$</td>
</tr>
<tr>
<td>Ratio $\bar{p}/\text{total}$</td>
<td>0.34</td>
<td>0.13</td>
<td>0.03</td>
<td>0.005</td>
</tr>
<tr>
<td>Flux inside $r \leq 5$ mm at target $\bar{p}$</td>
<td>$6.50 \times 10^7$</td>
<td>$4.20 \times 10^7$</td>
<td>$1.51 \times 10^7$</td>
<td>$1.92 \times 10^7$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>$1.56 \times 10^6$</td>
<td>$5.27 \times 10^6$</td>
<td>$3.68 \times 10^6$</td>
<td>$5.25 \times 10^6$</td>
</tr>
<tr>
<td>Ratio $\bar{p}/\text{total}$</td>
<td>0.32</td>
<td>0.11</td>
<td>0.04</td>
<td>0.006</td>
</tr>
<tr>
<td>Flux inside $r \leq 2$ mm at target $\bar{p}$</td>
<td>$1.85 \times 10^7$</td>
<td>$1.13 \times 10^7$</td>
<td>$3.51 \times 10^7$</td>
<td>$7.75 \times 10^7$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>$3.66 \times 10^6$</td>
<td>$9.33 \times 10^6$</td>
<td>$9.86 \times 10^6$</td>
<td>$9.32 \times 10^6$</td>
</tr>
<tr>
<td>Ratio $\bar{p}/\text{total}$</td>
<td>0.34</td>
<td>0.11</td>
<td>0.03</td>
<td>0.008</td>
</tr>
</tbody>
</table>

3.4 Electron-photon beam

The geometry of the target station has been designed with a view to providing essentially pure electron beams in either the H2 or H4 lines.

The scheme uses the decay into $\gamma$'s of $\eta^0$ produced in the target, the third magnet of the wobbling station being used to deviate the primary beam and to sweep away the charged secondaries.

The $\gamma$'s, in turn, produce electrons in a converter, which can be moved into one beam or the other in front of the first bending magnet.
A 4 mm thick lead plate or a silicon crystal can be selected as converter. The silicon crystal, after correct alignment with respect to its principal axes, has been found to enhance the electron flux by a factor of \( \approx 1.2 \) at 150 GeV/c compared to when the amorphous lead converter was used.

Figure 9 shows the electron fluxes from 400 and 450 GeV/c primary protons using a correctly oriented 50 mm thick silicon crystal as converter. The curves have been normalized to experimental measurements made in the H4 beam and scaled to the H2 beam acceptance.

At the downstream end of the beam, the electrons can in turn be used to produce a photon beam by bremsstrahlung in a radiator, similar to the converter, followed by a sweeping magnet. This magnet can be used to analyse the electrons issuing from the radiator if they are subsequently detected in a position-sensitive electron calorimeter array. The energy difference of the electron before and after the radiator yields a measure of the energy of the corresponding photon. The layout of such a tagging system, intended to be installed upstream of EHS, is shown in Fig. 10.

The expected photon beam spectra are represented in Fig. 11 for electron beams of 150 and 200 GeV/c, respectively, incident on a 0.1 radiation length radiator.

An appreciable enhancement of the high-energy end of the photon spectrum may be obtained, according to calculations\(^{16}\), by using an oriented silicon crystal radiator giving coherent bremsstrahlung, on condition that the electron beam divergence is kept small in one plane. This offers an interesting possibility for EHS, where the incident beam may be made relatively large and parallel in the vertical plane, whilst keeping the facility of collimating the photons in the horizontal plane (Fig. 10).

4. POSSIBLE FUTURE DEVELOPMENTS

A complete list of possible future beam development for EHS cannot be attempted. In this section a few possibilities which have received at least some consideration are mentioned.

The development at CERN of the high-rate production, cooling, and accelerating of antiprotons for the p\(\overline{p}\) experiments in the SPS has led to extracted, high-energy, pure antiproton beams for fixed target experiments to be considered\(^{11}\). Such an operation could provide EHS with \( \approx 10^7 \overline{p}/s \), with a duty cycle of \( \gtrsim 0.1 \) and momentum between 300 GeV/c and \( \approx 400 \) GeV/c.

The extracted \( \overline{p} \) beam might be used to provide a virtually pure, wide-band, antineutron beam by charge exchange in a target placed \( \sim 20 \) m upstream of EHS. A flux of \( 10^7 \overline{p} \) would provide \( \gtrsim 10^5 \overline{n} \) in a \( \pm 1 \) mrad cone (i.e. in a \( \sim 20 \) mm spot at EHS) and with mean energy \( \sim 80\% \) of the \( \overline{p} \) energy.

Such a project to provide high-energy extracted antiproton beams from the SPS has been shown to be feasible\(^{12}\), but has at present not been recommended by the SPSC.

A wide-band neutron beam could be produced by primary protons interacting in a target some 200 m upstream of EHS. Radiation and background levels in the experimental hall would limit the incident proton flux to \( \sim 10^{11}/s \), and this would yield \( \sim 10^7 \) n/s in \( \pm 0.1 \) mrad, giving again a \( \pm 20 \) mm spot at EHS. The mean neutron energy would be \( \sim 80\% \) of the proton beam energy. This idea could be attractive for future high-sensitivity experiments with EHS since present incident flux limitations would be less severe for neutral particles.
The possibility has been studied of using the secondary $\pi^-$ beam to provide a $K_L^0$ beam from a subsidiary target positioned $\sim 30$ m upstream of EHS\textsuperscript{13}). With a $\pi^-$ flux of $\sim 10^8$ $\pi^-$/s at 225 GeV/c, the $K_L^0$ flux is expected to be $\sim 3 \times 10^4$ with momentum between 70 and 210 GeV/c within a production angle $\sim \pm 1$ mrad. Such a $\pi^-$ flux in the H2 beam would require $\sim 5 \times 10^{12}$ 450 GeV/c primary protons incident on the primary target. The accompanying photon flux of $\sim 7 \times 10^5$ from $\pi^0$ decays could be used as an untagged alternative to the tagged bremsstrahlung beam already discussed in the previous section. Approximately half the photons would have energy $> 60$ GeV.

A difficult possibility, but attractive from the viewpoint of charm-hyperon production\textsuperscript{14}), is one that would require a high-energy negative hyperon beam. Based on extrapolations from existing beams, it is estimated that a $\Sigma^-/\pi^-$ ratio of $\sim 0.15$ at 350 GeV/c with a beam intensity of $\sim 10^6$/s may be obtained. Neutral hyperon beams would again offer the advantage of a neutral beam for EHS; however, in this case, neutron contamination would limit the $\Lambda/n$ ratio to $\sim 0.03$.

The layout implications and background problems associated with some of these ideas would have to be investigated further if they were to become realistic options for EHS.

Acknowledgements

The authors wish to acknowledge the contributions and support received from their colleagues of the CERN/SPS-EA Groups and of the EHS Collaborations in the running of the H2 beam.
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Fig. 1 Layout and optics of H2 beam to EHN 1 -- High-resolution mode

Fig. 2 Target station T2
For primary Proton momentum = 400 GeV/c

Moments which can be obtained at production angle:
Θ = 0 are indicated by solid lines
0 < Θ < 4 mrad "broken" - - - - - -

Fig. 3 Possible combinations of particles and range of momenta of beams from target station T2
Fig. 4 Range and coupling of momenta of beams H2 and H4 (hadrons) from target station T2. EPB = 400 GeV/c.

Fig. 5 Beam H2 total particle fluxes
Fig. 6  a) Schema of the rotating collimator and b) diagram of beam modulation

Fig. 7  Schematic optics of beam H2 in filter mode
Fig. 8 Pressure scan for CEDAR No. 1 (beam H2) with 0.3 mm diaphragm

Fig. 9 Electron flux in beam H2 per $3 \times 10^{12}$ incident protons (converter = 50 mm thick Si crystal)
Fig. 10 Schematic layout of γ-tagging system for HOLEBC + EHS (beam H2)

Fig. 11 Integrated photon spectra from H2 electron beam with 0.1 X₀ radiator
A PROGRAMME FOR HIGH-RESOLUTION RESEARCH  
WITH THE EUROPEAN HYBRID SPECTROMETER IN 1982-1983:  
A SUMMARY  

L. Montanet  
CERN, Geneva, Switzerland.  

1. OUR AIM  
- To determine accurately the properties of the short-lived (\(\sim 10^{-13} \text{ s}\)) particles (c, b, ..., \(\tau\) ...):  
  - lifetimes,  
  - branching ratios (Cabibbo-allowed or not),  
  - spectroscopy: D\(^*\), \(\Lambda\_c\), \(\Lambda\_c\)\(^*\), ... .  
- To study production mechanisms (hadronic and photonic):  
  - cross-sections (SPS/ISR),  
  - correlations (short-range, flavour flow, ...),  
  - diffraction/fragmentation/central production,  
  - dependence upon \(E\_\text{inc}\), quark\(\text{inc}\), \(A\), ... .  

2. WHAT DO WE NEED?  
- Resolution of the vertex detector:  
  50 \(\mu\text{m}\) for \(\tau = 8 \times 10^{-13} \text{ s}\),  
  20 \(\mu\text{m}\) for \(\tau = 2 \times 10^{-13} \text{ s}\),  
  10 \(\mu\text{m}\) for \(\tau = 10^{-13} \text{ s}\).  
These numbers (the first two at least) are based on experience, scanning efficiencies, etc., for bubble-chamber film with good contrast, hadronic production at SPS energies, etc.  
- Rates, i.e. not necessarily \(10^6\) events badly reconstructed, but a few hundreds of well-constrained, well-identified events.  
  Two factors can be considered:  
  a) The intrinsic rate of data acquisition given by rapid-cycling bubble chambers, including scanning-analysis rates (not useful to produce \(10^6\) events if we can digest \(10^6/\text{year}\)!).  
  b) Acceptance of downstream spectrometer, gamma detectors, particle identifiers, which are essential for the identification of rare events.  

With HOLEBC + EHS, classical optics, and hadron beams, we can expect:  
- 20 tracks/expansion, duty cycle \(\sim 2\%, 30 \text{ Hz}\),  
- 10 cm of H\(_2\), interaction trigger of \(\sim 20 \text{ mb}\)  
  + 1 evt/\(\mu\text{b/day}\)  
(at least the same rate with RCBC, and probably more).  

With HOLEBC holography, these rates may be increased by 20 to 50 but a more sophisticated trigger will then be necessary.
3. ACCOMPLISHED IN 1979--1981

1979 - NA13 - "bare" LEBE = 50 $\mu$m, 13 'candidates' + cross-section.
1980 - NA16 - LEBE + EHS + $D^0$, $D^\pm$ lifetimes and production characteristics.
1981 - NA26 - HOLEBC + EHS = 20 $\mu$m with classical optics.

4. PLANS FOR 1982

- To accumulate a few hundreds of $D^0$, $D^\pm$, and a few tens of $F^\pm$, $\Lambda_c^+$, with HOLEBC (classical optics) and EHS.
15 days of 360 GeV $\pi^+p$ and 15 days of 360 GeV/c proton-proton, giving $10^6$ pictures.
The total of completely reconstructed c's could be of the order of 50 $F^\pm$, 150 $D^\pm$, 150 $D^0$, 100 $\Lambda_c^+$.
- To test RCBC with three normal views plus one high-resolution channel giving $\sim 35 \mu$m over 40 cm (and only used for scanning).
$10^6$ pictures taken with RCBC could provide $> 150$ $D^\pm$ completely reconstructed, the associated charm being searched for by effective mass and kinematics.

5. PHOTOPRODUCTION IN 1983

Using HOLEBC in the holographic mode ($R < 10 \mu$m) triggering on hard photons and hadronic final states, a sensitivity of 10 evt/nb could be reached. Many technical questions need to be solved (holography, tagged photon beam, trigger, electromagnetic background, upgrading of spectrometer for $\sim 70$ GeV incident particles, etc.).

If technically feasible, this experiment could provide several thousands of c's and several tens of b's.

I believe that such a major step should be taken in the best possible conditions, by adding to the spectrometer a good streamer chamber in the vertex magnet of EHS (see E. Johansson's talk). This streamer chamber would increase significantly the acceptance and efficiency for low-momentum tracks, would allow the detection of a sizeable fraction of strange particles associated with c's and b's, and could provide particle identification.

6. MORE PROPOSALS

With the advent of high-resolution bubble chambers and the completion of EHS (more particle identification, gamma detection, calorimetry), we have a beautiful tool to study heavy flavours. There are many other possibilities than those discussed above (see Niels Doble's talk on beam possibilities). We need more proposals.
SCANNING AND MEASURING BUBBLE CHAMBER HOLOGRAMS

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Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Rome Italy.

1 - INTRODUCTION

Just few days before the beginning of this workshop the first high energy experiment using an holographic bubble chamber as high resolution vertex detector has completed its first test run. Although it is too early to attempt a detailed discussion and comparison of the various possible approaches to the problem of scanning and measuring high energy interaction holograms, I will try in this note to discuss some of the basic requirements and of the expected performances of an holographic scanning and measuring machine. In the following I will also assume that the main aim of the scanning will be the search for the decay of short living particles and that the measurements will be used to link the tracks observed in the bubble chamber with a downstream spectrometer.

2 - SCANNING

The main difference between classical picture and hologram scanning arises from the need of using a TV camera for inspecting the event instead of the standard projection of the image on a table\(^1\). As a consequence of this we have to face three main problems in the search for secondary activity:

a) limited field of view;

b) kink detection with the main interaction vertex possibly outside of the TV screen and without the horizontal projection;

c) confused regions (many nearby tracks) that are normally disentangled with the head-on view on the horizontal projection.

Extrapolating from a typical bubble chamber experiment searching for short-lived particle decays (CERN NA16 experiment) we can assume that the two basic magnifications needed for an efficient scanning are (magnification = image on the TV vidicon/real space; to this one has to add a \(\sim x 30\) electronic magnification):

\[ \text{MAG1} = 1 \]

for a general view of the event (resolution is not important).

---

1) The projection of holograms, although possible, requires very high laser power and is affected from speckles. (See Rutherford Proceedings on Holography applied to Bubble Chamber Physics-RL-81-042)
MAG2 > 3 for short decay detection (with full resolution implying a bubble diameter at least of the same size of the spot on the TV vidicon, i.e. ~ 30 μm).

In both these conditions the field of view is definitely too small being 1 and 0.3 cm (of real space), respectively, in the beam direction.

In order to solve the field of view problem and the lack of horizontal projection, there are two proposed solutions:

a) anamorphism, i.e. MAG (y) = n MAG (x) with n of the order of $4^2$. This trick, (that can be easily realized electronically with a TV camera), increasing the track to track separation in the forward jet is of great help in disentangling confused regions;

b) the "swing" table for kink detection, first proposed from S.Natali (University of Bari). The principle of the table is very simple; in addition to the three standard xyz movements there are two additional degrees of freedom: a rotation around the optical axis of the TV system and a very precise "swing" in a fixed direction on the xy plane. After having centered the main vertex on the optical axis, the track under inspection for kink is oriented (with the rotation) in the swing direction and then the stage is swung back and forth along the track. Any kink will show up as a displacement of the track from the reference cross. The whole operation is very fast and can be therefore done systematically on all the secondary tracks.

A sketch of a prototype of this table is shown in Fig.1; in this case the two additional degrees of freedom are obtained mechanically but many other solutions (optical for example) are possible\(^4\).

The sensitivity of the method (assuming a minimum detectable displacement equal to a bubble radius, i.e. 5 μm) corresponds to an average detectable $L \sin \theta_{\text{DECAY}} = 10 \, \mu \text{m}^2$. Obviously the swing has to be done in full resolution condition (i.e. MAG2) and is limited to an $L \sin \theta_{\text{PROD}}$ range of the order of the depth of focus of the image of the TV screen (but this can be overcome with a computer assisted swing with an additional movement in the z direction).

With a) + b) scanning on the TV screen can be expected to have comparable speed respect to a conventional scanning and has the advantage of being more reliable, if the swing is done systematically. Obviously the efficiency for detecting far away decays (like $\nu^0$) will be lower than in

\begin{itemize}
  \item \text{See RL-81-042 - H.Drevvermann and J.R.Lutz contributions.}
  \item \text{See J.R.Lutz contribution to this workshop.}
  \item \text{For the definition of these quantities see for example: G.Ciapetti contribution to the Vezeelay workshop on high resolution CERN/EP/EHS/PH 80-2.}
\end{itemize}
the conventional scanning but this does not seem to be a serious limitation because the short lived decays will normally be in one TV field and $K^0/\Lambda^0$ decays are anyway expected to happen outside the bubble chamber (the linear dimensions of an high resolution holographic bubble chamber cannot exceed 10-20 cm).

3 - MEASUREMENTS

As it has been said in the introduction the main aim of the measurement is the "hooking" of the tracks seen in the bubble chamber with some external device for momentum analysis. In a typical spectrometer like the EHS one a good hooking efficiency can be obtained if the angular errors on the tracks are at the level of 0.1 mrad in $\phi$ and 0.7 mrad in dip. These figures for a track length of $\sim 5$ cm imply a measurement accuracy better than 5 $\mu$m in $y$ and 35 $\mu$m in $z$.

The 5 $\mu$m accuracy in $y$ can be easily achieved provide that the bubble image on the vidicon is 3-4 times bigger than the reference cross (spot size, i.e. 30 $\mu$m). This implies a third magnification for the measurements (MAG3 10).

For the $z$ accuracy the situation is not so easy. The holographic image of a 10 m bubble is expected to be 100-200 $\mu$m long in the $z$ direction, making a 30 $\mu$m requirement in accuracy quite difficult to achieve. More over a MAG3 level may be not enough for a good focusing. It is worthwhile to mention that P. Poropat (Trieste University) claims for a $z$ accuracy in the range of 20 $\mu$m focusing the black spot that appears in the center of the bubble image when the magnification is pushed up to $\sim 30$.

4 - SUMMARY OF THE HOLOGRAPHIC MACHINES

Many machines for scanning and measuring holograms are at present in an advanced status of realization in Europe. Table 1 summarizes the main characteristics of the projects.

All of them are in-line machines (but switchable to the two beam scheme) and all (but one) are using TV for looking to the image. The xyz stage is computer controlled and should be able to center a given point and to follow a straight line in space within few microns. Anamorphism and graphic facilities on the screens will also be available.

---
5) See P.F. Smith - RL-81-042.
5 - CONCLUSIONS

Scanning and measuring holograms of high energy interactions on a TV screen with acceptable speed and good efficiency seems at present a manageable problem provide that a certain number of tricks are implemented in the apparatus. The first generation of machines that are coming into operation will define soon a certain number of basic specifications for such a type of devices.

Table 1

<table>
<thead>
<tr>
<th>MOVEMENTS</th>
<th>LASER</th>
<th>CLAMPING</th>
<th>MAG1</th>
<th>MAG2</th>
<th>MAG3</th>
</tr>
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<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>z</td>
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<td></td>
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<td>FILM</td>
<td>FILM</td>
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<td>MIRROR</td>
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<td>GLASSES</td>
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<td>FILM</td>
<td>TV</td>
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<td>He Ne 5mW</td>
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</tr>
<tr>
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<td>FILM</td>
<td>FILM</td>
<td>FILM</td>
<td>ARGON 10mW</td>
<td>VACUUM</td>
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<tr>
<td>ROME</td>
<td>FILM</td>
<td>TV</td>
<td>TV</td>
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<td>FILM</td>
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<td>FILM</td>
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<tr>
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<td>FILM</td>
<td>LENS</td>
<td>He Ne 5mW</td>
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<tr>
<td>TRIESTE</td>
<td>TV</td>
<td>TV</td>
<td>MIRROR</td>
<td>He Ne 5mW</td>
<td>VACUUM</td>
</tr>
</tbody>
</table>

(*) 150 on Table

(**) 500/30
Fig. 1 Bari scanning and measuring apparatus for HOBC holograms (NA25)
Hologram Scanning and Measuring Device

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Abstract
In the High Energy Physics area, the charm hunting needs the use of holography to perform recording of optical information with high resolution and large depth of field. The scanning and measuring of bubble chamber holograms reveal a bunch of problems, occurred either by the holographic technique itself or by recorded event topology.

The kink detection, the magnification, the optical and video improvements and the "Z" motion will be checked. The final lay-out with the optical, video, and mechanical set-up will be described.

Introduction
At the previous meeting on the Application of Holographic Techniques to Bubble Chamber Physics, held at Rutherford Laboratories in January 1981, we presented ideas and tests to solve some of the emerging problems to scan and measure holograms. Now, we check deeper the problems and describe our lay-out for a holographic scanning and measuring device.

1. The Third Dimension
1.1 The "Z" Motion

The X and Y motion is a well known and solved problem in standard measuring device. As this motion can be done in a horizontal plane the moving mass is not critical. The "Z" depth motion, orthogonal to the previous ones is then vertical. One can minimize the vertical moving mass, or fold horizontally, by mean of a mirror, the vertical light beam (lengthening the optical path). In fact, the following solutions are possible:

- moving the film gate
- moving the camera with its lens
- moving a set of mirrors
- moving only an object lens whereas the camera and the camera lens remain steady.

We use the last set-up. In this case
- the moving mass is low
- the moving lens position is disconnected from the steady camera position
- the use of a zooming lens here allows zooming on several cameras with different magnifications.
1.2 The "Z" localization

It is sometimes difficult to locate an information in depth in the hologram. Thus, the use of multi-synchronized cameras set up has been tested, each of these displaying another plane in depth. The picture of each camera is displayed in another colour on the same colour video monitor.

Thus, the operator sees 2 or 3 successive superimposed planes of the hologram, each in a different colour and with a defined depth of field. Moving in depth to find an event shows successive patterns where the colour of the focused plane looks bright and sharp on the background coloured fringes of the out-of-focus planes. By this way, it should be easy to get a reflex knowledge for backward or forward motion on "Z" axis.
2. THE MAGNIFICATION

2.1 The optical magnification

The choice of the right magnification is very important for the performance of the scanning/measuring device. Assuming that we give up the optical display for speckle and laser power problems, the first order parameter for resolution in video technique is defined by the vidicon characteristics: about 600 to 800 discrete discernable lines in the middle of its target. This number is coherent with the number of scanlines (625 at all, but only 575 are really used to pick up the picture). For a standard 3 x 4 TV picture, an area of about 12 x 16 mm can be scanned on the vidicon target. The resolution is then 20 to 25 microns in each direction. If 5 microns bubbles must be seen, a 4 times linear optical magnification must be achieved by the lens (if the reconstructed hologram has the same size as the object). That means also that the displayed part of the bubble chamber represents a 12/4 x 16/4 = 3 x 4 mm area for 5 microns resolution.

Thus, a low optical magnification (< 4)
- locates macro information easily
- but loss of the resolution because of the vidicon target characteristics

A high optical magnification (> 4)
- shows no loss of resolution
- but information is difficult to locate because only a small area is displayed

A motion in X and Y direction to scan the whole fiducial volume seems inconvenient. A better solution is to use several video cameras to get simultaneously different magnifications. One can also use a zoom lens on one or several cameras.

Our solution uses one ZOOM lens only for several cameras, which performs a 25 times optical continuous magnification range. For example, a range from 0.8 times to 20 times displays an area from 15 x 20 mm to 0.6 x 0.8 mm.

The VIDEO magnification, about 20 times, must obviously be added.

Our choice

The WILD M400 MACRO-ZOOM lens 3) has been chosen. The focus range is 1 to 5 i.e. a focus length from 50 mm to 250 mm. The object focusing distance to the front plane is 102 mm. The numerical aperture is 0.027 to 0.115. Additional lenses extend from 0.5 to 2 x the upper characteristics. The overall magnification is M = F2/F1,

F1 being the object ZOOM lens focus length and
F2 being the camera lens focus length

Thus, for a "one camera set up", we would choose the magnification range 1.5 to 7.5 times or 2 to 10 times.

For, a "two cameras set up", although a continuous magnification range from 0.8 to 20 times can be achieved, an overlapping of the camera ranges leads to the following magnifications.

Camera 1 : 1 to 5 times (12 x 16 to 2.4 x 3.2 mm)
Camera 2 : 3 to 15 times (4 x 5.3 to 0.8 x 1 mm)
THE OPTICAL ZOOMING

CAMERA 1

CAMERA 2
Superimposing the two pictures in two different colours should be tested. It could allow to check easily if a straight track goes on to the vertex or not (see 3.3).

2.2 The Video Camera A.G.C. improvements

In an "in line" bubble chamber hologram, the energy of a focused track is very high. Furthermore, there is an important variation of the background density within the hologram, and a rough step of full intensity light between the holograms during the film motion. The Automatic Gain Control circuitry is in charge of adjusting the vidicon sensitivity to the grey level scale, i.e. to the light variations. This contrast control function must be very performing and tuned for the considered holograms.

2.3 The Video Camera resolution improvements

The quality of scanning and measuring is strongly related with the quality of the video camera. That's why we improved its resolution.

The video display screen size is a fixed parameter. So, increasing the correlated target size improves the resolution by increasing each pixel size on the vidicon. This is done by increasing the gain of the deviation amplifiers which improves the scanned area size by a ratio of two at least.
2.4 The switchable ANAMORPHOSIS \(^{1,2}\)

As pointed out in January 1981 at the RUTHERFORD Meeting on Holographic Techniques, the standard 3 x 4 TV picture ratio may not be the best one for high energy purposes. The events generally present a jet pattern and "opening" the event separates the different tracks. Furthermore, the goal of charm detection needs good sensitivity to small angular deviations. These purposes are performed by ANAMORPHOSIS, that means by squeezing the particle beam direction (Y) and stretching the perpendicular direction (X). This has been done in our video cameras by switching the gain of the deviation amplifiers, tuning thus the scan-line length and distance on the vidicon target, the scanning of the video monitor remaining standard. A \(X/Y\) magnification ratio of 4 can easily be reached but care must be taken to the scanned area size. A too small size burns out the vidicon target. We chose the following values.

- Useful one inch vidicon target diameter : 20 mm
- Standard scan size : \(8 \times 12 = 108 \text{ mm}^2\)
- Improved " " : \(12 \times 16 = 192 \text{ mm}^2\)
- Anamorphosized " : \(20 \times 7 = 140 \text{ mm}^2\)
ANAMORPHOSIS

Vidicon target size

standard scanning size

correlated displayed area on the T.V. screen

anamorphosed scanning size

correlated displayed area on the T.V. screen

Displayed pictures
3. THE KINK DETECTION

3.1 The ANAMORPHOSIS

The switchable anamorphosis of our cameras improves by itself the direct kink detection. Nevertheless, its efficiency is limited to a few degrees.

3.2 The Radius Technique

Sergio Natali, from Bari (Italy) developed a new strategy of kink hunting, performed by mechanical translation and rotation of his film gate.

He assumes that the considered tracks are straight lines and the aim is to find tracks which miss the vertex, looking from their end.

The idea takes use of the integration in time operated by the vidicon, the display screen and the human eye. Thus, moving fast along a straight track parallel to it, shows a continuous straight steady line whereas background and non parallel or crossing tracks disappear at all or show moving flares.

The kink hunting sequence is the following

- Localization of the vertex
- Positioning the vertex in the rotation center of the device
- Translation onto the end of the event.
- Positioning the track on the reference cross by rotating the event around the vertex which remains in the rotation center of the device
- Fast translation from the end of the track towards the vertex along a straight line.

If the track has no kink, it is displayed as a steady straight line.

If there is a kink, i.e. a deviation compared to the straight line, the display shows the deviation as a shift on the screen. The displayed line moves perpendicular to its direction. This principle is very sensitive for kink projections on a X Y plane.

A variation of this technique can be used if a kink is suspected.

- One places the rotation center on the track "after" the supposed kink
- One detects the end of the track by translation and rotation and moves along it to be sure that it is well positioned.
- One goes toward the vertex and looks if the vertex is missed or not.

The same process can be performed by software control of the stages motions in real time.

We perform this technique by an optical way which requires no real time computing power for scanning, and no sophisticated mechanical motions. The rotation is done by a WOLLASTON device whereas the translation occurs by reflection on a rotating mirror. The results can be compared to those of the mechanical set-up. The use of anamorphosis should even increase the sensitivity.
TRANSLATING AN EVENT ALONG A GIVEN DIRECTION FROM LEFT TO RIGHT BY MEAN OF A ROTATING MIRROR

Optical magnification : 5x
Displayed area : 2.4 x 3.2 mm
3.3 The superposition technique

This technique consists in superposing one wide angle video picture in one colour with a second small angle video picture from a second camera in another colour on the same colour display. The wide angle camera shows the general sharp track direction which is compared to the local track direction given by the small angle camera.

One can always know where the vertex is, and a kink should appear as no parallel display of the track in the two colours.

This idea is an extrapolation of that developed on a graphic basis by H. Drevermann at C.E.R.N.⁹, but we did not test it yet.

4. The general lay-out

As shown in the picture, one can mention the following components in the present status.

4.1 The laser ⁶)

- SPECTRA - PHYSICS MODEL 120 (USA)
- Hélium-Néon Red
- 5 mW at 632,8 nm
- Telescope SPECTRA - PHYSICS MODEL 332 with a lens of F = 6.1 mm and a pin hole diameter of 15 µm
- Lens for parallel beam with focus length: F = 140 mm; diameter: 63 mm
- Beam diameter: about 30 mm

4.2 The film gate

Vacuum film clamping is used

4.3 The X, Y motion

It is horizontal and moves the film gate. Measuring least count is 2 microns.

4.4 The zoom lens ³)

- WILD M 400 (Switzerland)
- It has been described earlier. Its motion is vertical over a length of about 100 mm.
- The focal range is 5.

4.5 The video cameras ⁷)

- SOFRETIC (France) 1 Inch Vidicon tube
- 625 2:1 interlaced scan lines
- Automatic sensitivity control range 1000/1
- Target sensitivity: 2 Lux (.2 Foot-candle)
- Resolution in center: 750 points
- Scanning direction switchable top-bottom, left-right
- Anamorphosis 4/1 Switchable (modification made)
4.6 The other components

- One WOLLASTON diameter : 30 mm
- One rotating mirror
- One camera lens $F = 250$ mm for low magnification
- One camera lens $F = 750$ mm for high magnification
- One semi-transparent mirror to split the light to the two cameras used for the moment.

CONCLUSION

The suggested set-up is in the test status now. It should be considered as a step for a scanning and measuring device. In the final state one can imagine that the full power of colour video displays could be used to feed a maximum of useful information for the operator ("Z" localization, different magnifications superimposed, alphanumeric messages, graphic information, touch panel, light pen and so on). Main improvements can be done on the real time process control and data acquisition of the device. Autofocusing and optical or video filtering should be tested.

ACKNOWLEDGEMENTS

I am indebted to H. Drevermann (C.E.R.N.), K. Geissler (C.E.R.N.) and S. Natali (Bari) for useful discussions, as well as to the people whose help enabled the described construction.

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THE HOLMES PROJECT

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CERN, Geneva, Switzerland.

1. INTRODUCTION

HOLMES is a working prototype of a scanning and measuring machine for HOBC holograms. The machine is connected via CAMAC electronics, a MII-11 microcomputer, and a serial link to a VAX computer. The scanning process is based on the use of TV displays.

We have made extensive use of the existing film-measuring machine spiral reader (SR) and its electronics, which have been out of use for two years. To the existing x-y stages of the SR we added an independent, lightweight, ballscrew-driven stage for z movement. The incremental encoders on the three stages have least counts of 2 μm in the x and y, and 4 μm in the z direction. Stage movements are controlled by means of a track ball for x and y, and by a wheel for z. Maximum travel time from one point on the picture to any other is 2 s.

The essential features of HOLMES are outlined in Fig. 1. To scan HOBC in-line holograms conveniently we need a choice of different magnifications of the reconstructed image, as has been demonstrated already on a series of NA16 images shown at the Rutherford meeting in January 1981. For the general survey and scanning purpose as well as frame number reading we use normal high-resolution 1 in. TV cameras. There is a particular need for an anamorphic display which opens up the particle jet image to an aspect ratio of 1:4. Furthermore, we use a high-magnification display for precise positioning. The general arrangement of these displays around the operator is shown in Fig. 2.

Since there is not much space available (90 mm) between the film clamp and the reconstructed image, we use a transfer lens (Componon 180 mm, f:5.6) to situate the image plane at a convenient place, where there is ample space to locate beam splitters, spatial filter wires, the cursor illumination system, and the TV cameras.

The operation of HOLMES is straightforward. We move the hologram in the x and y directions, but for movement in the z direction we move the linear z stage with its two-mirror set to bring planes at different depths in the bubble chamber to focus in the transferred image plane.

The greater part of the parallel laser light illuminating the hologram is still "unused" by the in-line hologram and as such forms a useless background illumination behind the image (see dotted lines in Fig. 1). This parallel light is concentrated by the transfer lens at its focal point and may be stopped there by a blackened needle or a similar beam stopper, acting as a spatial filter.

2. CAMERAS AND MONITORS

Camera A (Bosch TYK9A) shows an area of Lx = 7.2 mm × Ly = 10 mm on the film as well as in the space of the reconstructed image; x is parallel to the beam direction. Camera A is used by the operator
a) to stop the film at the right position and to show the picture number,
b) to find and roughly centre the fiducials,
c) to find and roughly centre the predicted beam track,
d) to investigate all secondary tracks at large angles from the beam direction,
e) to find secondary vertices at large angles (Fig. 3a),
f) to show highly ionizing tracks if spatial filtering is used for camera B (see below).

The spread in y of 11 mm is just sufficient to show the last three digits of the picture number without moving the picture. When showing the picture number the x-y stage is driven to the expected picture number position and the camera is focused by the z stage onto the film plane which is illuminated by the laser.

The camera is equipped with a vidicon and has an automatic gain control (AGC). It is connected to a standard TV monitor (monitor 1).

Camera B (Hamamatsu C1000-16) was specially modified by Hamamatsu to provide an anamorphic display of the picture. The magnification perpendicular to the beam direction (y) is about five times larger than along the beam (x).

The camera displays an area of \( L_x = 11 \text{ mm} \times L_y = 2.8 \text{ mm} \) in the real image. It is used

a) to resolve the secondary tracks in the jet (Fig. 3b),
b) to detect and verify secondary vertices.

It is practically impossible to disentangle the tracks in the jet using camera A rather than camera B (compare Figs. 3a with 3b and 4b with 4d).

Owing to the small visible area in y (\( L_y = 2.8 \text{ mm} \)) and the anamorphism (which cannot be modified) the camera can neither be used to read the picture number nor to investigate easily tracks at large angles (compare Figs. 3a and 3b). If a spatial filter is used, highly ionizing tracks become invisible. Hence the necessity of using the two cameras A and B.

Since camera B has no AGC the operator is provided with a control of laser intensity in case the film density varies.

Camera B can be connected by operator control either to the normal TV monitor or to the graphics monitor. A small mirror on the table in front of the monitor allows inspection of the monitor screen at a shallow angle as can be done when scanning on a table. For small kinks this turned out to be helpful. We will investigate whether a monitor screen which is not perpendicular to the view of the operator is advantageous.

Camera C (Bosch TYK9A) shows an area of \( L_x = 0.8 \text{ mm} \times L_y = 1.3 \text{ mm} \). It is used

a) to focus (z measurements),
b) to measure x and y precisely,
c) to magnify the interaction region,
d) to resolve close tracks (Fig. 3c).

This camera has an AGC and can be connected by operator control to monitor 1 or 2.
3. SPATIAL FILTERING

As described above, a spatial filter has been used successfully. It consists of a straight wire passing in the y direction through the focus of the transfer lens; compare Figs. 4a and 4c with 4b and 4d. It has the following advantages:

a) The background is more uniform.
b) From large objects the edges only are visible.
c) The signal-to-noise ratio is much improved.
d) By use of the wire instead of a point, linear structures in the x direction are eliminated (scratches on film, etc.).
e) The focusing precision is higher (see below).
f) The smaller focal depth helps in detecting kinks in z, which are not visible in the x-y plane.
g) Highly ionizing tracks, especially in the beam direction, are filtered out.
h) The change in density at the edge of the picture gives problems when inspecting the TV image, as one part of the image is too light and the other too dark. The spatial filter solves this problem (otherwise a mask must be used which needs a precise film stop).

It has the following disadvantages:

a) A higher laser intensity is needed.
b) The focal depth is reduced so that one must scan in different z planes.
c) The image of the fiducials is of less good quality.
d) The picture number is not visible.

The resolution on camera B seems to be as good as without the spatial filter. Spatial filtering for camera C will soon be tried.

A spatial filter which can be moved in and out by the operator might be more useful.

4. z MEASUREMENT

The focusing (z) is done purely manually. Table 1 shows the r.m.s. of 22 z measurements of the same bubble string for the three cameras with and without the spatial filter, which cannot yet be used for camera C because of insufficient laser intensity. The measurement of the focal depth being very subjective is only qualitative.

<table>
<thead>
<tr>
<th>Camera</th>
<th>A</th>
<th>A</th>
<th>B</th>
<th>B</th>
<th>C</th>
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<td>Spatial filter</td>
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</tr>
<tr>
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<td>7.5</td>
<td>12.5</td>
<td>12.5</td>
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<tr>
<td>Ly (mm)</td>
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<td>11</td>
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<td>3</td>
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<td>r.m.s. (µm)</td>
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<td>Max. error (µm)</td>
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<td>Focal depth (mm)</td>
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<td>1.5</td>
<td>2</td>
<td>1</td>
<td>1</td>
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</table>
The relatively high precision of positioning in z obtained with camera C compared to that with cameras A and B justifies its use.

However, the precision in z is still much worse than in x or y (some microns). If the light cone of the individual bubbles is not parallel to the z axis, a condition which might be produced by a wrong adjustment of the z stage, an error in x and y will result from the difficulty of focusing. The same is true if the film is not perpendicular to the laser beam when exposing the hologram. Illumination of the bubble chamber by a convergent laser beam produces the same effect if the light is not made parallel before reaching the film. This may necessitate a different coordinate system (R, θ, φ) for the software or maybe even for the stage movements.

Owing to the big difference in precision between x, y, and z, all errors, fit parameters, offset parameters, etc., are calculated separately for x, y, and z.

5. VERIFICATION OF SECONDARY VERTICES

Many secondary vertices are not clearly visible and outgoing secondary tracks must often be checked. To establish whether they originate from the primary or secondary vertex, two methods are possible:

i) By measuring one point on the track a line in space between the track point and one of the vertices is calculated. Visual inspection (see below) then shows whether the real track and the calculated line coincide.

ii) By measuring two points on the track portion behind the suspected kink the calculated offset parameter may be used for a decision or one may follow the line backwards to check whether it passes through the vertex. In this way the position of very small kinks may be found.

Two methods are available to check whether the track and the calculated line coincide:

a) A graphic line is overlaid onto the video image (Fig. 5a). This method works only if the kinks are visible in the x-y projection.

Only the overlay of a straight line through the centre of the monitor is needed. The magnification of the video image and the graphic picture need not be equal! (if no graphic monitor exists, one may try to overlay an optically produced rotatable line via a semi-transparent mirror onto the monitor).

b) A mechanical movement along the calculated line allows a check in space. It is more precise as it avoids distortions of the optical system and the TV cameras. However, it is much more time consuming than method (a).

In practice the movement along the line is done by reading every 20 ms the desired movement from one direction (x) of a track ball. From this the appropriate movements of the three stages x, y, z are calculated and executed.

The speed and ease of method (a) is improved in the following way: one cross which is fixed in the middle of the screen indicates the measuring position. A second cross is moved instantaneously with the position of the x-y stage (properly scaled down). It indicates automatically the direction and the distance to the vertex (Fig. 5b). If a track is centred
on the middle cross, it originates from the vertex only if the moving cross is also centred on the track. Moreover, the vertex may always be recovered if one moves the second to the first cross. On the vertex itself the crosses are superimposed.

6. **SCANNING PROCEDURES**

   i) Manual measurement of one fiducial (the predicted track is shown automatically).

   ii) Search for and measurement of a beam track (only a movement along the known beam direction is possible).

   iii) The vertex is found.

   iv) The vertex is measured.

   v) Search for secondary vertices. Several methods can be used:

      a) Continue movement in beam direction for optical inspection. The width (y) of the area shown on camera B is larger than the "charm box". If spatial filtering is used this must be repeated for different z values.

      b) Check any track on the graphic monitor to see whether it coincides with the two crosses.

      c) Check any track in space by mechanical movement along line.

   vi) If a candidate is found it may turn out to be necessary to check it carefully by the mechanical movement along the predicted line. By using two points per track the kink point or secondary vertex may be found.

   vii) If one candidate is found a more careful search for a second one may be necessary [points (vb) or (vc)].

   viii) The relevant tracks can be measured with many points. Kinks, etc., can be found by investigating the residuals to a straight line fit.

   The time to scan an event depends heavily on the methods used; this means whether a visual inspection only is performed [continue with (vi) after (va)] or whether the much more complicated methods (vb) and/or (vc) are used too.

   The boundaries of the scanning volume in the x-y plane are indicated on the graph monitor as normally no fiducials to define the scanning volume are visible.

7. **FUTURE DEVELOPMENT PROGRAMME**

   - Improvement of adjustment.
   - Study of spatial filtering.
   - Continuation of scanning (so far 236 pictures with 95 events have been scanned).
   - Provision of a cursor on all monitors.
   - Study of double beam holography.
   - New (cheaper) graphical overlay.
   - Automatic focusing.
   - Holography of big chambers (BEBC).
Fig. 1 Outline of the essential features of the HOLMES prototype of a scanning and measuring machine for in-line holograms

Fig. 2 Arrangement of the general purpose, anamorphic and graphics monitors, computer terminal, x-y track ball, z wheel, and machine control keyboard in front of the operator
Fig. 3 The same event is seen (a) with camera A, (b) with camera B, and (c) with camera C connected to the normal monitor, while in (d) the same event is seen with camera B connected to the graphical monitor. Spatial filtering is not used in any of the four pictures.
Fig. 4 The same $V^0$ is seen (a) and (b) on camera A, and (c) and (d) on camera B. The position of the decay point is indicated by an arrow. The spatial filter is not used in (a) and (c). In (b) and (d) it is used.
Fig. 5  a) Graphic overlay of a line onto a track which does not originate from the primary vertex. b) By use of the fixed small cross and the moving big cross, the origin of secondary tracks is checked. All pictures are taken using camera B without spatial filter.
A MEASURING DEVICE FOR HOLOGRAMS FROM LARGE VOLUME BUBBLE CHAMBERS

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ABSTRACT
Measuring full-size reconstructed holographic images of bubbles from a large bubble chamber presents problems of size, rapid location of the desired event, and precise measurement of a local region. We present a conceptual design of a practical system using computer-controlled mirrors to align the desired vertex region along the axis of motion of a vidicon whose field of view includes the local region. Precise measurements of short-decay paths are then made by fine adjustments of the vidicon position. This method requires normal stereo photography for scanning and preliminary reconstruction of the event.

INTRODUCTION
The advantages of high resolution in detecting short-lifetime decays, and the advantages of holographic photography in preserving depth of field with high resolution, are well known. The use of small bubble chambers with holographic photography has been demonstrated in hadron beams; e.g., by the BEBC group. Progress has been made with somewhat larger chambers (e.g., the HOLEBC chamber development), also designed for use with hadron beams. In this area of small or medium-sized bubble chambers (or streamer chambers) for use with hadron or photon beams, where the volume to be photographed is small, holography has been pushed with the greatest vigor and with promise of early success.

In neutrino physics the beam-target volume cannot be made small; neutrino beams are difficult to focus or collimate. Yet neutrino interactions are one of the cleanest and best sources of charmed particles, and "beautiful" particles are expected at higher energies; Charm plus Beauty yields at the Tevatron should constitute at least 10% of neutrino events, as compared to 1% of photon interactions and 0.1% for hadron beams. Thus, for bubble chambers, which can accommodate only a few interactions per picture, a large bubble chamber in an intense neutrino beam may be more useful for studying charm and beauty events in detail than a small chamber rapidly cycled in a hadron or photon beam.

As an example, the approved E646 15-foot bubble-chamber heavy-liquid (Ne-H$_2$) experiment planned for the Tevatron beam dump anticipates the following number of events in a 200,000-picture run with $2 \times 10^{18}$ protons of 1000 GeV energy incident on the dump:

- 1200 tau neutrino CC interactions
- 5600 electron neutrino CC interactions
- 8400 CC muon neutrino events
- 10 "beauty" particles

The prompt neutrino interaction yield per incident proton expected in E646 with 1000 GeV proton is estimated to be $\approx$ 100 times greater than previous BEBC beam-dump experiments at 400 GeV. The prime objective is to verify the existence of the tau neutrino and study its interactions. A systematic study of electron neutrino interactions is also feasible. If the mystery of "neutrino oscillations" is not yet solved by Tevatron turnon, this beam-dump experiment's results on the relative numbers of $\nu_\mu$, $\nu_e$, and $\nu_\tau$ events may contribute to the solution.
The advantages of holography are clearly indicated for Tevatron neutrino beams in bubble chambers: with the present 15-foot conventional optics, the bubble size and resolution are about 500 microns. (The resolution can be improved to ~200 microns by sacrificing depth-of-field.) Due to the short lifetime of the tau, only a small fraction of tau decays is expected to be visible decays with conventional optics. With holography one can hope to achieve resolution better than 50 microns over the full-chamber volume. Since the median decay distance for the tau-lepton in the Tevatron beam-dump experiment is about 800 microns, holography can improve both the yield and quality of the detectable signal for taus. It may also make it possible to detect "beauty" decays, which are expected to have even shorter decay distances.

**PROBLEMS WITH LARGE VOLUME HOLOGRAPHY**

Holographic photography over a large volume poses difficulties not encountered with small volumes where "direct-view" holography (i.e., film area comparable to cross section being photographed) is practicable. The Welford scheme of two-beam holography in Scotchlight-illuminated bubble chambers has been tested at RHEL\(^1\) and at BEBC\(^2\) and appears to be feasible, but requires special optics and modifications to the chamber. A different method has been proposed by Baltay\(^3\) for the 15-foot chamber as shown in Fig. 1: the laser beam enters at the bottom of the chamber via a diverging lens, and the direct and scattered amplitudes are recorded on the film without any focusing lenses. Preliminary bench tests of this idea at Columbia appear encouraging, and an engineering test with the 15-foot chamber at Fermilab is planned in 1982.

Another problem with large-volume holography is connected with **viewing** and **measuring** the holographic image. In principle, when the hologram is projected with CW laser light, the full-size bubble images will be produced in space over the original volume of the bubble chamber. The 20 m\(^3\) fiducial volume of the 15-foot chamber presents quite a problem to scan for small bubbles! Furthermore, conventional measuring methods would require moving a high-precision measuring device over large regions of space. This is obviously impractical.

We have devised a scheme for avoiding these problems, which appears to us to be practical. First of all, one does not scan the holographic image but relies on conventional three-view pictures (the three "normal" stereo cameras of low resolution) to locate interesting events. Stereo reconstruction determines their spatial coordinates with the usual precision of bubble-chamber event reconstruction. Secondly, one uses this information to establish which specific region of holographic image space should be viewed at high magnification. Mirrors are adjusted (by computer control) to view the vertex (or other restricted region of interest). Precise measurements can then be made of decay distances on the full-size bubble image.

A schematic drawing of the proposed system is shown in Fig. 2. The hologram is illuminated with a CW laser of nearly the same wavelength as the pulsed laser used in the initial exposure. This will reproduce the real bubble image in space by the interference of coherent light from all parts of the hologram. The total image will occupy a volume in
space relative to the hologram corresponding to the bubble-chamber volume, including angles up to 40 degrees from the optic axis. However, by using plane mirrors tilted at the proper angle, the image in question can be brought into the "measuring volume" where the vidicon is located. This "measuring volume" is cylindrical with its axis located above a one-dimensional track upon which the vidicon cart rides. This cart can be moved to bring the image within the field of view of the vidicon, and the magnified image can be displayed on a TV monitor.

This method has the advantage that the mirror directs the narrow cone of interference rays from the hologram in the direction of the vidicon, so that only a slight swiveling of the vidicon is required to align it for optimum viewing. A lens can be used between the bubble's real image and the vidicon for greater magnification. Measurement of the decay distances can be made on the TV monitor, or directly in space by moving the vidicon with the points in question centered in the field of view.

Computer-controlled motion is essential for this scheme to work, and the spatial coordinates of the localized region must be known reasonably accurately in advance from the stereo photographs.

SOME CRITICAL ELEMENTS OF THE MEASURING MACHINE

The mirrors involved must be very flat, and their motion smoothly and accurately controlled. The angular accuracy of mirror setting required to position the image of a bubble well within the aperture of a vidicon (2.5 cm) at a typical distance of 400 cm is only \( \approx 1 \) milliradian; such mechanical motion (two angles) is easily made and measured. Incremental shaft encoders with accuracies of better than 1 part in \( 10^5 \) per revolution are now available. Thus with computer control of mirror position the vertex can be positioned accurately within the field of view and moved about with computer control.

The measurements on the reprojected image can be made either (1) on the magnified CRT image or (2) by moving the vidicon by precision x-y stage to bring several points to the center of the vidicon (cross hair). The former method is more convenient but the linearity and CRT are not involved. In the latter method, the non-linearities of the vidicon movement is the only limitation. In either case the image of bubble on the vidicon may be magnified: typically, x10 at the vidicon and x200 on the CRT. Thus a 50 micron diameter bubble image would appear as 500 microns at the vidicon and 10 mm on the CRT. This is a convenient scale for viewing and making measurements. Short-decay distances would be magnified to a scale where their detection would be readily done on the CRT; angles could be enhanced by making the transverse magnification greater than the longitudinal magnification.

STATUS OF THE PROPOSED MEASURING MACHINE

At the present time this is just a proposal, although development funds have been sought and a preliminary design has been sketched. It is our intention to compare this proposal with other methods of measuring large-chamber holograms during this conference, and then choose the best method for further development for the 15-foot chamber holograms.
ACKNOWLEDGMENTS

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* * *

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3) "Improved Optics for the 15-Foot Chamber," remarks by C. Baltay at Fermilab meeting in April 1981.

![Diagram of holography in 15' chamber](Fig. 1)
THERMOPLASTIC FILM CAMERA FOR HOLOGRAPHIC RECORDING

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ABSTRACT
The design thermoplastic-film recording camera and its performance for holography of extended objects are reported. Special corona geometry and accurate control of development heat by constant current heating and high resolution measurement of the develop temperature make easy recording of reproducible, large aperture holograms possible. The experimental results give the transfer characteristics, the diffraction efficiency characteristics and the spatial frequency response.

1. INTRODUCTION

Usually, an optical recording medium requires a certain processing to transform the recorded information into a form that is suitable for readout. In some applications, like Optical Memories (1), Optical Information processing (2) and Holographic Interferometry (3), this processing should be preferably done inside the recording configuration. In industrial applications, e.g. of the holography, the processing time should be as short as possible.

The conventional silver halide emulsions do not meet these requirements. Their processing, consisting of wet chemical development and fixation, usually can not be accomplished in the recording setup. A repositioning of the processed plate of film into the optical setup with an accuracy up to some fractions of the optical wavelength is very critical, and troublesome.

In the past two decades, this limited potentiality of conventional photographic materials has brought many investigators to explore the possibilities of new types of recording media. It was shown that the use of photothermoplastic materials for recording offers significant advantages due to the combination of the following properties of thermoplastic materials:

1. A considerably low value of the exposure energy is needed.
2. The diffraction efficiency is rather high.
3. The recording of information and processing for readout can be done in situ, so that no repositioning troubles are met.
4. If desired, the recorded information can be erased, and the material is then reusable for the next recording.

Experiments with a thermoplastic material on a glass carrier for information storage have started as early as 1959 (4). In the recent time a photothermoplastic film with a plastic carrier was developed, which is better suitable for industrial applications than the plate. Also cameras using the photothermoplastic film were introduced.

Nevertheless, some further optimization of this recording technique and the instrumentation are still necessary, to make them useful for high repetition rate laboratory experiments, for industrial applications and for difficult holographic recordings with large aperture.
2. PHOTOThERMOPLASTIC FILM

The photothermoplastic film (e.g. Kalle PT-1000) consists of three layers (5). On the transparent plastic carrier a thin photoconductive layer is deposited, which is covered finally by a thin layer of the thermoplastic material.

For sensitizing the film, the surface of thermoplastic material is uniformly electrically charged. During the recording, the intensity distribution of the incident light produces a conductivity pattern in the photoconductive layer which results in a charge redistribution on the surface of the thermoplastic material. The surface-charge distribution produces finally a pattern of electrostatic forces in the thermoplastic material which is a replica of the light-intensity pattern to be recorded.

To develop the force pattern, the thermoplastic material has to be heated slightly above its melting point. Becoming soft, the surface is deformed under the influence of the electrostatic forces until at each point an equilibrium between the surface tension forces and the electrostatic forces is obtained. Being cooled down under the melting temperature, the thermoplastic material hardens again and the surface deformation becomes fixed. The surface of the developed film becomes slightly milky as if frosted.

To perform the phase transition of melting, a certain amount of heat must be delivered to the thermoplastic layer. This has to be done rather quickly to avoid surface charge loss due to conductivity of the thermoplastic material which rises drastically near the melting point. To obtain a fast softening, the material is heated for a short time far above the real melting temperature to pump the necessary develop heat into the thermoplastic layer in a very short time.

To reconstruct the information, now stored in the form of the thickness variation of the thermoplastic, the film is illuminated with a readout laser beam. The phase of this beam will be changed according to the stored thickness variation, which corresponds to a phasehologram.

When heated beyond the melting temperature, the thermoplastic material softens so far, that the stored information is erased. Theoretically, the film could be used after cooling for a next record. This is nevertheless not recommendable due to successive degradation of the thermoplastic layer and to possible ghost pictures due to imperfect erasing.

To obtain a homogenous film sensitivity across the whole active area, the surface charge has to be perfectly uniform. According to theoretical predictions (6), the sensitivity of the film depends at least quadratically on the electric field or the charge density. Usually, the surface has to be charged to several hundreds of volts. The easiest way to do it is by means of a corona discharge in air.

3. CAMERA

The camera consists of a mechanical body and of an electronic control unit. The mechanical arrangement and the functions of the camera body are based on the well proven principles and the design as described by R. Moraw (5). We have optimized our camera especially for industrial applications of holographic interferometry. The recording aperture of the camera is 70 x 50 mm. The method we use consists of successive stages of charging, exposure and development.
In the mechanical body, the thermoplastic film is stretched across a carrier plate, made of insulating material. A glass plate with a vacuum deposited, transparent resistive layer on the surface is embedded in the carrier plate in such a way, that the film is guided exactly along its coated surface. The resistive layer on the plate is equipped with contacts in the form of thicker, vacuum deposited conductive strips along two parallel edges of the plate. Two thick copper mesh strips are pressed by rubber cushions against these plate contacts. One of the plate contacts is grounded.

During the sensitizing phase, a carriage with a linear array of needles for corona charging is slowly moved at a constant distance along the film surface. The static charge on the film provides also for its firm adhesion on the glass. For film transport, the carriage lifts the adhering film from the surface of the glass plate and a motor-winder transports the film.

To assure a perfectly uniform charge distribution on the film surface and thus a uniform sensitivity across the film area, a relatively dense linear array of needles with a precisely defined radius has to be used. We found as an optimum a radius of 0.2 mm and a separation of 2.5 mm. The array has to be somewhat longer then the film-width to reduce edge effects. The peaks of the needles have to be adjusted to lie exactly on a straight line. The distance of the peaks to the thermoplastic surface has to be optimized for a given voltage to allow for homogenous charge distribution without any charge concentration in the central part of the film area and to prevent local break downs.

Massive breakdowns would damage the transparent resistive layer on the glass, if the output capacitor of the HV power supply could be discharged into the thin layer without a current limitation. To minimize this damage, a HV resistor of several tens of megohms is inserted into the lead from the HV power supply to the array of needles on the carriage.

After sensitizing, a waiting time of several seconds is necessary before exposure, to allow the mechanical vibrations of the whole camera body to die away.

For development, a current pulse is fed to the resistive layer on the glass plate, which acts as a resistive heater and simultaneously as a resistive temperature sensor, allowing to measure the temperature of the heater and to turn off the heating at the appropriate moment. The temperature coefficient of the optically transparent resistive layer (Balzers Aurell-A3) is nevertheless very low, about +600 ppm/deg C. To measure the turn-off temperature accurately, a high resolution resistance bridge is needed.

Fig.1 shows the simplified circuit diagram of the electronic development control, we use successfully in our photothermoplastic cameras.

The resistance Rp of the heater builds together with a shunt Rs and the resistors R11, R21, R12, R22 (SW3 open) a Thomson bridge, which eliminates errors due to the resistance of the wiring. The value of Rs is 2 Ohms, the other resistors are kOhm values, being 1000x larger than Rp and Rs. The copper mesh strips are connected on one side to the development-current source, the opposite ends are connected to the bridge circuit.

The bridge circuit, adjusted for balance at Td, is used to detect the achievement of the develop temperature Td and to turn off the heating current. It should be mentioned here, that the develop temperature Td should not be understood as the softening temperature of the thermoplastic material, but rather as the heater temperature at which heating is to be turned off.
With a new heater plate inserted, the bridge has to be pre-balanced first, as the heater resistance has a manufacturing tolerance of some +/- 20% around the nominal value of 15 ohms.

A floating voltage source source PS2 of a few volts is used to feed the bridge without causing a significant warmup of the heater during the balancing (SW2 closed, SW3 open, T1 nonconducting). With SW3 open, the bridge is balanced if

\[ \frac{R_p(T_a)}{R_s} = \frac{R_{11}}{R_{12}} = \frac{R_{21}}{R_{22}} \]

where \( R_p(T_a) \) stands for the heater resistance at the ambient temperature \( T_a \), at which the bridge was balanced.

The setting of the resistances \( R_{11} \) and \( R_{21} \) is ganged for proper balancing of the bridge. Each resistance is a series combination of low temperature coefficient (15 ppm/deg C) precision resistors, which are switched in steps and of a helipop potentiometer. The precision comparator C (e.g. a uA 734) and a light emitting diode LED serve as a balance indicator.

At the develop temperature \( T_d \), the value of \( R_p \) will be

\[ R_p(T_d) = R_p(T_a) \cdot (1 + k (T_d - T_a)) \]

where \( k \) stands for the temperature coefficient of the heater layer.

To obtain balance at \( T_d \), the value of \( R_{12} \) is decreased (SW3 now closed, potentiometer \( R_{12} \) in parallel to \( R_{12} \) to

\[ R_{12}' = \frac{R_{12}}{1 + k (T_d - T_a)} \]

where \( R_{12}' \) is the parallel combination of \( R_{12} \) and \( R_{12} \),

\[ R_{12}' = \frac{R_{12} \times R_{12}}{R_{12} + R_{12}} \]

A slight mismatch in the ratio \( R_{21}/R_{22} \) (\( R_{22} \) not being changed correspondingly with \( R_{12} \)) decreases marginally the suppression of the wiring resistance; this effect is of no importance, as the resistance change of \( R_p \) between \( T_a \) and \( T_d \) is very small.

The correct setting for \( T_d \) can be hardly calculated, as the necessary temperature overshoot for development depends on many parameters like rate of temperature change, thickness of the film carrier layer etc ... Thus, the setting for \( T_d \) has to be found experimentally. Once found at any ambient temperature \( T_a \), it keeps valid for any initial conditions of the heater temperature.

The bridge circuitry and the comparator are placed in a screening box in the camera body. Besides that, the camera body contains a remote controlled HV power supply for the corona charging. All other circuitry is placed in the electronic control unit, which is connected to the camera body by a cable.

From the control unit, only the development-current source in shown in a simplified form in Fig. 1. A floating power-supply PS1 charges over a current limiting resistor R1 the electrolytic capacitor C1 = 72,000 uF to 140 volts. A constant-current circuit, consisting of transistor T1, resistor R2 and a Zener diode ZD1 can deliver between 5 to 6 Amps into the heater plate. The current source can be turned on and off by the set-reset flip-flop F-F which controls the optocoupler O.C. and the transistor T2 (both saturated or off). The collector current of T2 feeds the Zener diode ZD1 and turns thus T1 on.
For development, the flipflop F-F is set by a short pulse to turn on the heating. The bridge remains unbalanced and the comparator output high, until Td is reached. Then the comparator resets the flipflop and terminates the heating.

With a constant heating current, the rate of change of the thermoplastic temperature is also approximately constant. Obviously, the higher the rate of change of the temperature of the heater, the larger will be the lag in the rise of the temperature of the thermoplastic itself, as the heat is transferred from the heater to the thermoplastic by conduction through the film carrier and the photoresistive layer. At the moment, when the thermoplastic reaches its melting temperature, the heater has already a temperature overshoot due to the mentioned lag and naturally some amount of heat is stored in other components like glass plate etc. All these overshoot effects can be compensated by a proper setting of the develop (turn-off) temperature Td. With different initial conditions of temperature, the duration of the heating pulse will vary, but the develop heat will remain constant.

In the practical circuit, 5 transistors 2N6259 with separate emitter resistors are used in a Darlington stage as T1, to prevent second break-down if a short-circuit across the load should occur. As the capacitor C1 prevents only a limited amount of energy, no thermal destruction of the camera could occur even if the electronic switch should fail to open due to some defect in the circuitry. On the other hand, the capacitor must be large enough, to allow to keep the heating current constant until the end of the development, i.e. under typical laboratory conditions between 100 and 400 msec.

The electronic control unit controls all other camera functions.

During the sensitizing phase, the film transport and corona charging is controlled. The corona voltage Vc can be preset in the range between 5 kV and 15 kV.

A shutter control allows for a time preset between 50 msec and 5 sec or for a permanent opening of the shutter. For an optimum reproducibility of the holograms, we use an integrating exposure meter with energy preset for the shutter control (7).

The preset of the develop temperature is done with a helipot potentiometer in the control unit.

After the dry thermal development, a cooling timer with a time preset between 20 sec and 500 sec is started automatically. The fixation of the hologram can be done either by ambient air only, or by forced cooling. In the latter case, a set of fringes may arise due to shrinking effects.

As any running function inhibits automatically a start of any other function, repeated attempts of development in short time intervals, which could damage the plate are also disabled.

We use the same electronics for the large aperture camera of 70 x 50 mm and also for the small aperture camera of 35 x 50 mm. For the small aperture camera only, a capacitor C1 of 24,000 uf is sufficient; only 3 power transistors are needed as T1 and the heating current can be reduced to 4 to 5 Amps.

4. EXPERIMENTAL RESULTS

The experimental results are shown for the use of this thermoplastic film camera in an holographic system. Three tests have been chosen: (1) the transfer characteristics; (2) the
diffraction efficiency characteristics; and (3) the spatial frequency response.

Holograms of a diffusely illuminated two-dimensional object were made with approximately 21 deg angle between the object beam and the reference beam R1 and 24 deg for the reference beam R2. The recording and reconstruction wavelengths for all results presented in this paper were 514.5 nm and were recorded with the optical setup shown in Fig.2. In our experiments we used PT 1000S (8) photothermoplastic films with 35 x 50 mm and 70 x 50 mm as recording aperture.

Fig.3 shows the curve of brightness in the reconstructed image as a function of exposure for holograms of a diffused object. The exposure sensitivity of the film is high and comparable to that of high resolution photographic emulsions. We observed that increasing the potential to which the thermoplastic surface is charged tends to move the curve to lower exposures as predicted theoretically by Gaynor (6). The maximum occurs at an exposure of about 0.8 μJ/cm sq.

The most critical factor at the development stage is the thermoplastic develop heat. As mentioned above, this heat is determined primarily by the rate of change of temperature during the heating and by the develop temperature Td, at which the heating is turned off. This turn-off temperature is always higher than the melting temperature of the thermoplastic, as the melting heat has to be delivered to the thermoplastic in a very short time during this temperature overshoot. With different initial conditions of temperature, the duration of the heating puls will vary, but the develop heat will remain constant.

The dependence of the brightness of the reconstructed image on the develop temperature is given in Figs.4 and 5. These results, especially the one in Fig.4, show clearly that the reproducibility in the brightness of the reconstructed image of thermoplastic holograms depends very strongly on the develop heat and thus also on the develop temperature Td. On the other hand, the Fig.5 shows, that the duration of the heating puls has no significant influence on the brightness, as expected. A deviation of +/- 0.5 deg C from the optimum develop temperature results typically in a decrease of the brightness of the reconstructed image by 25%.

The constant-current heating controlled by a direct measurement of temperature allows to keep the develop temperature and thus also the develop heat reproducibly within a narrow limit independent of ambient temperature variations or undefined initial thermal conditions of the heater at repetition rates with intervals below 5 minutes. This results in only +/- 5% variation in brightness of the reconstructed image.

The specially designed corona geometry allows to improve the homogeneity of the efficiency over the recording frame. We have experimentally found that the variation of the efficiency over the recording area (70 x 50 mm) is about +/- 2%.

In order to measure the signal-to-noise ratio (SNR), we utilized as the object a white painted surface whose central part was covered with an opaque strip. The SNR was determined by scanning the reconstructed real image with a pinhole-photomultiplier tube assembly and by computing the ratio of the averaged intensities across the illuminated and the opaque part of the image. The result is given in Fig.3 and is obtained at a spatial frequency of 650 L/mm with the corona voltage Vc of 14.5 kV and a reference-to-signal beam ratio of 1. In Fig.6 the brightness in the reconstructed image at a spatial frequency of 650 L/mm is shown
as a function of the beam ratio. The maximal brightness in the reconstructed image is not coincident with the highest SNR.

To determine the diffraction efficiency we recorded holograms with a setup shown in Fig.2. Diffraction efficiency is the percentage of the incident light diffracted into the first order by the hologram. The maximum diffraction efficiency we achieved with PT 1000S for a diffused object was about 30% at a spatial frequency of 600 L/mm as it is shown in Fig.7.

In our holographic experiments with the PT 1000 type thermoplastic film we obtained for a diffuse object a band-pass response for spatial frequencies with a maximum at 550 L/mm and a useful range from 350 to about 900 L/mm as shown in Fig.8, where Io^2 (NORM) is the distribution of the brightness in the reconstructed image divided by the light distribution of the illuminated object. For these measurements, the same pinhole-photomultiplier tube assembly is used. Short exposure times lead to additional suppression of the higher frequencies. The knowledge of this response allows to estimate the maximum size of a recordable object as well as to design a special object illumination which compensates for the intensity losses at higher frequencies.

5. CONCLUSIONS

The thermoplastic recording medium has a considerable potential for many holographic applications. It offers ease and convenience to the rapid in situ process of recording and reconstructing of large aperture holograms.

The panchromatic and sensitive photoconductor gives the medium a response comparable to that of high resolution photographic emulsions. Furthermore, the thermoplastic forms relatively efficient thin phase holograms. The holograms can be formed over a broad range of exposures, but are much more sensitive to the develop heat. Although the sensitivity to the develop step is an inconvenience, it is relatively straightforward to use the constant-current resistive heating and a direct measurement of the heater temperature for an accurate develop heat control. Finally the addition of a special designed corona geometry permits rapid and uniform charging.

The investigations show that the performance of a thermoplastic film camera can be optimized to such an extent that even difficult holographic recordings with large apertures, e.g. as needed for industrial applications of dual reference-beam holography (9) and heterodyne holography (10), can be made in a routine manner.

We acknowledge the helpful discussions and support of R. Moraw and the technical assistance of P. Hefti and R. Kirchhofer who performed all the holographic tests.
REFERENCES

7) V. Masek: (to be published).

Fig. 1 Simplified circuit diagram of the development control
Fig. 2 Holographic set-up for the measurements of transfer characteristics, diffraction efficiency and spatial frequency response.

Fig. 3 Curve of brightness and SNR in the reconstructed image of thermoplastic holograms as a function of exposure energy.
Fig. 4 Experimental result showing the brightness in the reconstructed image versus develop temperature for different corona voltages $V_c$.

Fig. 5 Representative curve for develop temperature and different heating times.
Fig. 6 Brightness in the reconstructed image vs reference-to-signal beam ratio

Fig. 7 Graph showing the dependence of diffraction efficiency on exposure
Fig. 8 Dependence of brightness in the reconstructed image on spatial frequency with different exposure times
COMPUTER PROCESSING OF HOLOGRAMS*)

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Université Louis Pasteur, Strasbourg, France.

ABSTRACT

This process consists in the use of an image digitalizing system connected to a CRT or CCD camera. The software allows the transcription of the holographic data in geometrical data. Results are discussed.

*) The full text of this contribution was not made available for the Proceedings.
PRELIMINARY TESTS ON HOLOGRAPHY IN BEBC

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CERN, Geneva, Switzerland.

ABSTRACT
A collaboration has been set-up between the Institut de Recherche in St. Louis (ISL), the Rutherford Appleton Laboratory (RAL), and the BEBC Group at CERN to study possibilities for application of holographic techniques in BEBC. Laboratory tests and a first trial in BEBC have shown that holograms can be recorded with a two-beam set-up adapted to the optics system of the chamber. The object beam passing through the fish-eye windows illuminates the chamber; after reflection from the Scotchlite panel at the bottom of BEBC it falls through a large-aperture lens onto the film plane. The reference beam is projected directly onto the holographic film plane without passing through the chamber liquid. First results are presented on the influence of the BEBC magnetic field, vibrations of the BEBC expansion system, and on the limitations on resolution to be expected. An outlook is given of future plans for trying to feed a test program on holography into the physics program of the chamber.

1. INTRODUCTION

The ISL-RAL-BEBC Collaboration has been studying the possibilities for application of holographic techniques in BEBC\(^1\).

2. EXPERIMENTS AT ISL

At the beginning of this year several experiments were carried out at ISL by H. Royer\(^2\).

2.1 Set-up

Figure 1 shows the set-up provided in the laboratory. A krypton laser is used. The laser beam is divided by a prism into two beams: the object beam and the reference beam.

2.2 The object beam

After the beam splitter the object beam lights up a panel of Scotchlite, via small mirrors falls back on a lens, and finally illuminates the holographic plate which is between the real image and the lens.

2.3 The reference beam

After the beam splitter the reference beam lights up three mirrors and falls on the plate at an angle of about 30°. In fact the plate is inclined in order to be perpendicular to the angle of the two beams.

2.4 Characteristics of the set-up

<table>
<thead>
<tr>
<th>Distance object to lens</th>
<th>2 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance Scotchlite to lens</td>
<td>4 m</td>
</tr>
<tr>
<td>Total optical path</td>
<td>8.9 m</td>
</tr>
<tr>
<td>Diameter of the lens</td>
<td>150 mm</td>
</tr>
<tr>
<td>Focal length of the lens</td>
<td>750 mm</td>
</tr>
<tr>
<td>Aperture of the lens</td>
<td>F = 5</td>
</tr>
<tr>
<td>Diameter of the holographic image</td>
<td>50 mm</td>
</tr>
<tr>
<td>Demagnification</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Diameter of the illuminated Scotchlithe \(150 \text{ mm}\)
Wavelength of the krypton laser \(\lambda = 6470 \text{ Å}\)
Ratio of light between reference beam and object beam on the hologram \(2/1\)
\(1/25\)
Energy of the laser \(1.5 \text{ mJ}\)

2.5 Results of the experiment

Several holograms of 50 \(\mu\text{m}\) wires made of brass (see Fig. 2) were taken with a very good contrast and it is very difficult to perceive a difference between the real image and the holographic image.

The slides were taken from very poor polaroids but remain quite good.

3. EXPERIMENTS AT CERN

After these very encouraging tests which proved that with a very simple lens and Scotchlithe it was possible to see clearly wires of 50 \(\mu\text{m}\), we decided to plan an experiment in BEBC during a technical run in June\(^3\).

3.1 Experimental layout (Fig. 3)

The Big European Bubble Chamber (BEBC) in which first holographic tests were made contains 36 \(\text{m}^3\) of liquid hydrogen. The chamber body is surrounded by two superconducting coils providing a magnetic field of 35 \(\text{K}\).

On top of the chamber there are five windows, each consisting of three hemispherical components (fish-eyes). Two window components are made of quartz and the third component, which is in contact with the hydrogen, consists of BK7 optical glass. The interior of the chamber is covered with Scotchlithe, a material designed to reflect light along its incident direction with a very small angle of diffusion.

At the bottom of the chamber there is a floating disc hiding the moving piston which produces the necessary underpressure causing the liquid to boil along the particle track.

The operating conditions of the chamber during the holographic tests are given below:

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber liquid</td>
<td>(\text{H}_2)</td>
</tr>
<tr>
<td>Chamber temperature</td>
<td>26.8 (\text{K})</td>
</tr>
<tr>
<td>Chamber pressure</td>
<td>4.8 (\text{kg/cm}^2)</td>
</tr>
<tr>
<td>Refractive index of liquid</td>
<td>1.1</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>0 to 1.8 (\text{T})</td>
</tr>
<tr>
<td>Length of expansion cycle</td>
<td>100 ms</td>
</tr>
</tbody>
</table>

3.2 The set-up

The model of the set-up (Fig. 3) that we constructed was not very different from the one used at ISL.

3.3 The lasers

The compressors of BEBC generate heavy vibrations in the total area around the chamber. A pulsed laser is therefore needed to record the holograms even without the expansion system. The laser used was the ruby one built by H. Royer. Its characteristics are
Emitted wavelength \(6943 \, \text{Å}\)
Energy per pulse \(1.5 \times 10^{-3} \, \text{J}\)
Pulse duration \(20 \times 10^{-9} \, \text{s}\)
Coherence length \(1.5 \, \text{m}\)
Beam divergence \(0.5 \times 10^{-3} \, \text{rad}\)
Repetition rate \(0.02 \, \text{Hz}\)
Electronic trigger Pockels cell

In fact we needed a continuous krypton laser to align the ruby laser and the optical systems of the two beams.

3.4 The light beams

As already stated, we decided to choose holography with separated beams (see Fig. 3). The beam from the ruby laser is therefore split into two beams: an object beam and a reference beam.

The heavy shocks produced by the movements of the piston during expansion and the high magnetic field around the chamber are likely to upset the adjustment of the two lasers or even damage them.

The lasers therefore were placed far away from the centre of the chamber and on independent supports. Magnetic shielding was provided by AMCO casings, which also facilitated the pressurization demanded by the safety standards in a "hydrogen area".

The beam laser is separated into two beams by a beam splitter -- a glass prism of 30° angle -- reflecting 4% of the light on each surface. Therefore the transmitted light is 92%.

In fact we needed a telescopic system giving an enlargement of \(\frac{1}{2}\) to reduce the effects of the divergence and eliminate light losses.

3.5 Object beam

The beam transmitted through the beam splitter is subsequently passing via a mirror mounted on the camera frame to the bottom of the camera shaft at a distance of about 4 m. After bypassing mechanical obstacles constituted by the camera it illuminates, via a set of a prism and mirrors, and a diverging lens (f = -20 mm, diameter 10 mm), the bottom of the chamber (see Fig. 4).

Diffused by the Scotchlite the light is directed back through the fish-eye and the photographing lens (a 150 mm focal length component, f/5.6 aperture) illuminating the holographic film.

The entrance pupil of the photographic lens is mounted at the centre of curvature of the fish-eye to reduce the aberrations. The total optical distance of the object beam from the beam splitter is about 12 m.

3.6 Reference beam

The beam reflected by the beam splitter is used as a reference. The intensity of the beam is compared to the object beam intensity which is very low owing to the small aperture of the lens, to the Scotchlite, to the hydrogen, and to the fish-eyes.

As the reference beam is not passing inside the chamber, it has to have an optical path outside the chamber in order to satisfy the coherence conditions necessary for holographic
recording. The reference beam is sent to a mirror located about 3.5 m away from the beam splitter, returning after reflection and entering the camera shaft. At the bottom of the shaft a prism and mirror system reflects the beam on to the film via a short focal length diverging lens (f = -12 mm). The angle between the object beam, hitting the film at right angles, and the reference beam is 30°.

3.7 The holographic film

We decided to take holograms with one camera of BEBC, and we modified the camera mounted in the shaft number one. We used Agfa 10E75 film with the following characteristics:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>70 mm</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>185 μm</td>
</tr>
<tr>
<td>Backing</td>
<td>polyester</td>
</tr>
<tr>
<td>Perforation</td>
<td>standard but made to order</td>
</tr>
<tr>
<td>Spectral sensitivity</td>
<td>up to 750 nm</td>
</tr>
<tr>
<td>Absolute sensitivity</td>
<td>2 μJ/cm²</td>
</tr>
</tbody>
</table>

The film was developed in a Kodak versamatic automatic machine for 5 min using D19 developer at 30 °C. It was thus possible to double the sensitivity of the film as compared to normal development, so as to compensate for the low energy of the ruby laser.

4. PROBLEMS ENCOUNTERED DURING THE SETTING UP OF THE OPTICAL SYSTEM

We used an output power of 600 mW with a krypton laser. Unfortunately, the power losses, of the order of a factor of 1000 when passing the kryotr laser beam through the ruby laser, forced us, especially for the reference beam which used only 4% of the light, to install a third laser (helium neon) of 5 mW downstream of the ruby laser.

The different divergences of the krypton, of the helium neon, and of the ruby lasers required a systematic correction to be introduced into the adjustment of the afocal system. This correction could not be checked inside the camera shaft.

The coherent length of the ruby laser used is of the order of 1.5 m. The optical paths of the light in each beam (totalling more than 20 m) therefore had to be adjusted to within 10 cm to ensure that the fringes of the holograms were recorded with a contrast that was acceptable for the whole field. As the regions within the shaft and in the chamber (about 12 m) were completely inaccessible, the in situ measurements and the estimates according to the drawing had to be calculated very carefully to obtain the necessary precision.

The energy of the light pulse provided by the ruby laser is a basic parameter which cannot be altered during testing. The value we measured in situ was 1.5 mJ. There were no means to measure the energy received by the hologram from either the reference beam or the object beam. Tests performed with single and multiple exposures showed that the reference beam was luminous enough, but light intensity was lacking in the object beam. The diameter of the object field had therefore to be reduced to one quarter to assure a sufficient level on the hologram.

Realignment of the light beams on the 6 mm diameter diaphragm at the bottom of the camera shaft was also necessary when the magnetic field of the chamber was raised. Slight movements of the metal parts, due to the magnetic field, even on top of the chamber, required readjustment of the optical system.
Finally, the movement of the chamber expansion piston caused considerable vibrations which, with our layout of the optics, prevented us from recording holograms of tracks during chamber expansions.

5. RESULTS OBTAINED

5.1 Hologram without magnetic field or expansion

Figure 5a shows the hologram of the pupil of the photographic lens. As this aperture is lit only by the light reflected from the Scotchlite, some interesting conclusions may be drawn from this image. The luminosity of the image indicates that the fringes of the hologram have been recorded with good contrast, and that the difference of optical light paths between reference and object beams is still considerably less than the coherent length of the ruby laser for the field of view concerned.

The high-luminosity diffusion properties of the Scotchlite, already demonstrated in the preliminary tests without hydrogen, are confirmed. It also illustrates that the ratio of beam intensities, between reference and object beams recorded in the hologram, seems to be close to optimum).

5.2 Study of the effect of the magnetic field

Further holograms, taken at five different values of the magnetic field, show that the luminosity of the reconstituted images is remarkably stable. The values of the magnetic field were 0, 1000, 3000, 10,000 and 18,000 G.

5.3 Tests with expansion

As has been said, the vibration produced by the piston movements throws the set-up out of adjustment during the expansion cycle. It was thus impossible to record holograms in these conditions. Although this is a purely technical problem, it will have to be dealt with very carefully, in view of the considerable nuisance caused.

6. INTERPRETATION OF RESULTS OBTAINED

6.1 Laser energy

All holograms were recorded with a laser energy of 1.5 mJ. With this energy, only 1/16th of the desired total field could be illuminated. The losses by reflection, produced by the double passage of the object beam through the fish-eye, may be estimated at about 50%. Moreover, the aperture of the componon lens was fairly small at f/5.6. It would be feasible to fit a lens with double the aperture (f/2.8), giving adequate resolution with monochromatic light, and this would increase the light by a factor of four. Nevertheless it would be preferable to develop the film under normal conditions. A laser energy of 12 mJ would have to be used to holograph the intended total field of 1 m² in BEBC.

6.2 Image resolution

The small size of the reconstituted field prevented us from covering the area in BEBC where two 300 μm wires were stretched in the chamber. A 500 μm thick vertical wire reconstructed on the hologram with poor contrast (see Fig. 6) indicates that the small size of our lens aperture, spherical aberrations of the fish-eye windows, parasitic light reflected back from the window surfaces, and dust accumulated in the fish-eyes still represent severe
limitations that have to be overcome in the future. Finally, the difference in wavelength between recording and reconstituting the holograms may account for an additional loss of quality in the image.

Figure 7 shows that the reference beam was very dirty.

7. EXPERIMENTS WITH THE FISH-EYE AT THE RUTHERFORD APPLETON AND ISL LABORATORIES

After the experiment in BEBC we wanted to test the set-up in the laboratory especially with the fish-eye.

At Rutherford we used an argon laser. We took a hologram of a 125 µm wire with a very poor contrast; but the direct image was very poor too. We had many problems with the vibrations which prevented us from taking a hologram with a long exposure time.

At ISL we recorded a wire of 200 µm with a relatively good contrast. In fact it is very difficult to see a difference, once again, between the two pictures.

After these tests we could say that it was possible to record a wire of 300 µm in BEBC even with a fish-eye and with a standard lens if we had enough light.

8. LAST EXPERIMENT IN BEBC

We have just tried to take a hologram in BEBC with Royer's laser. We removed the camera from its shaft and used a very simple system with a holographic plate. Unfortunately the flash tube of the amplifier of the laser exploded and we could not record any hologram.

We tested our set-up with success during the expansions and we repeated the tests of May to see that the intensity given by the Scotchlite through the lens was the same at any value of the magnetic field between 20,000 G and 0 G.

We saw the fringes on the Scotchlite only moving, growing, and disappearing. These were probably due to the birefringence of the mylar which covered the Scotchlite.

9. CONCLUSIONS

We have come to the following conclusions:

i) The Scotchlite is very convenient for recording holograms in BEBC.

ii) The fish-eye with a very large aperture lens calculated to correct its spherical aberrations will give a resolution probably better than 80 µm in a volume of 1 m³.

iii) The Faraday effect will not prevent us from taking a hologram in BEBC.

In fact for our purpose we need a very powerful pulse laser which should be able to work in a magnetic field and during the expansions of the piston of the chamber.

We need to design a very sophisticated system to align the two beams in the very restricted space inside the fish-eye (a few mm), i.e. an electronic system.

It is also clear that we need to do many tests with a laser in the laboratory at CERN before starting a new experiment in BEBC.
REFERENCES

3) H. Royer, Microholographie dans un grand volume, possibilité d'application dans BEBC, unpublished.

Fig. 1 Layout of the test in the laboratory
Fig. 2  a) Picture from hologram of 50 μm wires  
b) Picture of 50 μm wires with classical optics
Fig. 3 Experimental layout at BEBC
Fig. 4 Holographic set-up at BEBC
Fig. 5  Holographic image of the pupil of the lens for several values of the magnetic field

Fig. 6  Holographic image of 500 μm wire

Fig. 7  Hologram of the reference beam
STATUS AND PLANS OF THE YALE-FNAL
HIGH RESOLUTION STREAMER CHAMBER COLLABORATION*)

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Yale University, New Haven, Connecticut, USA.

ABSTRACT

The Yale-FNAL High Resolution Streamer Chamber has undergone a number of modifications and improvements since its first operation in 1977. The chamber now operates with up to 175 kV (1.2 ns FWHM pulse) on a 0.45 cm gap at a maximum pressure of 40 atmospheres. The chamber gas is Ne/He/CO₂ (0.88/0.098/0.025) with the CO₂ added to suppress diffusion during the high voltage delay time. The chamber width and length are 3.0 and 4.0 cm, respectively. Photography of the streamers uses microchannel plate image intensifiers with optical gains of 10,000. Experiments are continuing on other chamber gas mixtures to improve track quality. A résumé of the performance characteristics of this chamber and a discussion of the limits of performance of chambers using self luminous photography will be presented. It will be shown that the use of the light scattering properties of the streamers is essential for significant improvements in the set of relevant chamber properties, i.e. size, gas pressure (target density), and track width. In particular, the use of holographic recording appears to offer great promise.

A brief analysis of the application of holographic recording to the problem of streamer photography will be presented. A promising, but as yet untested, approach appears to be the use of a laser tuned to one of the transitions of the neon metastable states. A comparison of the utility of the various transitions taking into account the existing data on oscillator strengths, pressure broadening, and metastable atom production in the streamer will be presented.

Finally, a brief status report on the current experimental program and the future plans of the Yale-FNAL Collaboration will be presented.

*) The full text of this contribution was not made available for the Proceedings.
SOME RESULTS FROM A SMALL HIGH-PRESSURE STREAMER CHAMBER

V. Eckardt* and S. Wenig*

ABSTRACT

In spite of the excellent results obtained for the accuracy and two-track resolution with emulsions and small bubble chambers, it is still interesting to use a streamer chamber (SC) for charm lifetime measurements because it is triggerable. A small SC with a track-sensitive volume of 50 mm diameter and 23 mm gap was constructed and operated between 5 and 20 atm pressure in the t_{s} test beam at the CERN Proton Synchrotron (PS). Streamer densities of 45 to 67 streamers per centimetre were found. The track width, which is determined by the diffusion of the electrons, shrinks proportionally to 1/\rho and reaches a mean displacement \sigma of 70 \mu m in space at 20 atm. Under certain kinematic conditions this allows a measurement of the charmed particle lifetime as short as 10^{-13} s.

1. APPARATUS

Figure 1 shows a schematic drawing of the set-up. The SC was positioned inside a magnet with 1.8 T field strength in the t_{s} beam line at the CERN PS. The trigger counters S_{1}, S_{2}, and S_{3} defined the particle trajectory within 2 mm horizontally and 10 mm vertically.

A brief description of the different components of the apparatus is given below.

1.1 The streamer chamber body

The design of the SC is determined by
i) the mechanical stability for the pressure up to 20 atm; and
ii) the insulation for the high electrical field strength.

The pressurized volume is therefore kept as small as possible, and the highest field is only in the track-sensitive area created (see Fig. 2). The high-pressure cell is positioned between the two HV electrodes, which have positive and negative polarity. Two specially shaped disks are mounted on these electrodes to create a homogeneous field of 50 mm diameter and 23 mm depth, and a glass window, 15 mm thick, is inserted in one of the electrodes. A grid with 0.05 mm thick wires and approximately 70\% transparency allows the streamers to be photographed along the electrical field lines. The grid electrode is covered by a thin Mylar foil to avoid discharges at the highest possible field strength of 150 kV/cm. The insulating wall is a Plexiglas ring, 30 mm thick. All measurements were done in a neon + helium (70\%-30\%) mixture. The surrounding ground electrode is a closed box, flushed at atmospheric pressure with SF_{6} or freon-12 during operation to avoid sparking.

1.2 The HV system

The HV pulses with positive and negative polarity are produced in a Marx generator and shaped in a double Blumlein pulse former to a length of 10 ns FWHM. The Marx generator has eight stages for each polarity; with 25 kV per stage, it produces ±200 kV. The two pulses have to arrive at the chamber simultaneously. Therefore, there is only one spark gap in the Blumlein system, with the discharge not grounded as usual but between the different polarities.

*) Visitor at CERN, Geneva, Switzerland.
1.3 Optics

The tracks were recorded on film. The camera was equipped with a 40 mm diameter two-stage image intensifier (2 × Varo 4215). The demagnification of 2.5 was chosen in order to provide a good resolution in space. With a 150 mm focal length lens from Rodenstock and an aperture of 5.6 we obtained a field depth of 3-4 mm. The limiting resolution of the lens and image intensifier system is > 40 LP/mm, and on Agfa film RP2 > 25 LP/mm. This gives a resolution of 100 μm and an accuracy of 10 μm in space. Figure 3 shows tracks at 5, 10, 15, and 20 atm pressure.

2. MEASURING PROCEDURE AND RESULTS

2.1 Measuring procedure

Tracks with similar contrast were selected, and the position of each streamer was measured on a Vanguard machine, which has a least count of 2 μm. A third-degree polynomial was then fitted to the measured points to eliminate optical distortions. The transverse distances from the points to the polynomial were calculated and the distribution fitted to a Gaussian to determine the mean displacement σ. Figure 4 shows the distributions for tracks at 5 and 20 atm.

In diffusion theory the mean displacement is defined as $\sigma = \sqrt{2Dt}$, where $D$ is the diffusion coefficient and $t$ the diffusion time, which for the SC is the time between the particle and the HV pulse. For different pressures $p$ this expression becomes,

$$\sigma = \sqrt{2D_0t p_0/p},$$

where $D_0$ is the diffusion coefficient at atmospheric pressure $p_0$.

2.2 Results

2.2.1 Streamer density

In a SC at atmospheric pressure and with a typical demagnification of 40-60, one counts typically two streamers per centimetre; this corresponds to 20% of the primary collisions in Ne-He (70%-50%), or less than 10% of the total ionization. With the high resolution optics and the very small streamers in the high-pressure chamber, it should be possible to record a larger percentage. Table 1 shows the streamer densities under various conditions.

Table 1

<table>
<thead>
<tr>
<th>Magnet (T)</th>
<th>Delay (μs)</th>
<th>Pressure (atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>0</td>
<td>0.6</td>
<td>43 ± 2</td>
</tr>
<tr>
<td>1.8</td>
<td>0.6</td>
<td>34 ± 1</td>
</tr>
<tr>
<td>Primary ionization per centimetre</td>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>
2.2.2 Track width at high pressure

From Eq. (1) we expect a reduction of the mean displacement \( \sigma \), i.e. the track width, proportional to \( \sqrt{p_0/p} \). Figures 5a and 5b show the measured \( \sigma \) as a function of pressure. The solid line is \( \sim \sqrt{p_0/p} \), which is in very good agreement with the measurement. At 20 atm a mean displacement \( \sigma \) of 70 \( \mu \)m is obtained.

2.2.3 The influence of a magnetic field

With an additional magnetic field the diffusion of the electrons should be further reduced owing to the Lorentz forces. The dashed line in Fig. 5a is an eye-guided fit through these measurements at a field strength of 1.8 T; it indicates a significant improvement only at 5 atm. At higher pressures the effect is negligible.

2.2.4 The influence of the primary electron energy and thermalization

After the collision of the particle with the atoms, the electrons have a primary energy which is higher than the thermal energy. Therefore the electrons move more at the beginning, before they are thermalized. This results in an additional track-broadening which is not described by the thermal diffusion. To investigate this effect, tracks were photographed with different delays and then measured. Figure 6 shows the \( \sigma^2 \) as function of the delay \( t \) for the different pressures. The extrapolation of the delay \( t \to 0 \) clearly indicates a contribution of this kind to the track width. Unfortunately the present data do not allow a more detailed analysis, and more measurements, especially at low pressures, are needed.

2.2 The shortest measurable lifetime

To determine the shortest measurable lifetime, a model calculation was made in the usual way: a decay vertex was defined if the extrapolation of the decay track missed the primary vertex by a distance \( a > 2\Delta a \), where \( \Delta a \) is the extrapolation uncertainty. A 20 mm long track at 20 atm was used, and the transverse distance to the decay track was calculated at a fixed decay angle \( \alpha \) and for different distances \( d \) between the primary and the decay vertex. If the condition \( a > 2\Delta a \) was satisfied, the flight path \( d \) could be determined by \( d = a \cdot \sin \alpha \). This distance \( d \) versus the decay angle \( \alpha \) is plotted in Fig. 7; the corresponding lifetime of the charmed particle is also indicated. It is assumed that the particle is produced at rest in the c.m.s. At a decay angle of 5° a decay length of \( < 400 \mu \)m is the shortest measurable distance, which corresponds to a lifetime of \( \sim 10^{-13} \) s.
Fig. 1 Experimental set-up (schematic)

Fig. 2 High-pressure streamer chamber inside the magnet
Fig. 3 Photographs of particle tracks at 5, 10, 15, and 20 atm
Fig. 4 Experimental distribution of displacements at 5 and 20 atm with the fitted Gaussian

Fig. 5 Mean displacement $\sigma$ versus a) pressure $p$ and b) $1/\sqrt{p}$
Fig. 6 $\sigma^2$ versus delay $t$ for 5, 10, 55, and 20 atm
Fig. 7 Shortest measurable decay length or lifetime as a function of the decay angle $\alpha$
Nd: YAG LASER FOR HOLOGRAPHY

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ABSTRACT
Different possibilities to use photonics, holography and optical processing for nuclear physics has been investigated in our works (1-4). The paper presents the results of the study of time and spatial coherence of Nd:YAG laser (5) and application in holography.

The yttrium-aluminium garnet laser doped with neodymium ions Nd:YAG, the wavelength 1.06 microns operating with gigantic pulses at high harmonics opens up new perspectives in holography due to the use of controllable transparens in data processing systems. The laser can operate at a very high frequency of pulses repetition with Q-modulation, up to 50 kHz, due to a high thermal conductivity of yttrium-aluminium garnet. Power of the gigantic pulses may reach about 100 MW with a quality factor as high as 1.5 percent, that is an order of value higher than for a ruby laser.

Coherence properties of the radiation are the basic criterion in applying a laser in holography. The object of the study was a serial laser that allowed us to obtain gigantic radiation pulses in the second harmonic at the length of the wave 0.53 microns at an energy E = 5 mJ, length 25 nsec and discrepancy 6 mrad (power 200 kW for \( \lambda = 0.53 \) mkm and 1 MW for \( \lambda = 1.06 \) mkm, pulses repetition frequency up to 100 Hz).

Both time and spatial coherence of the radiation has been studied by means of the Michelson interferometer. Generation spectrum width has been measured simultaneously using the Fabry-Perot interferometer. The laser beam passing through a collimator entered the Michelson interferometer with a variable length of one of its arms. It allowed us to vary relative delay from 0 to 100 cm. The interference pattern was recorded either photometrically or by a photomultiplier with the point diaphragm scanned normally to the direction of the interference friges.

The coherence degree /\gamma/ was determined by measuring the interference pattern contrast. Although photomoning of the interference pattern photos is known to be the simplest technique, nonlinearity of the photoemulsion sensitivity and inaccuracy in measuring the density of the film by the microphotometer result in more than 50 percent error. Direct photomering of the interference pattern by the photodetector is certain to be more accurate. In the experiment, use was made of the storing oscillograph operating in a storage mode to detect maximum and minimum intensities, the interference pattern intensity being averaged by a large number of pulses. The interference pattern shifted due to vibrations and the areas, differing in intensities from pulses to pulses, were detected by the photomultiplier with the diaphragm. Thus, we could see on the oscillograph a generation pulse with a blurred peak whose upper edge represents the maximum and the lower one -- the minimum of the interference pattern.

In Fig.1 the coherence degree /\gamma/ is plotted against relative delay of the interfering beams for energies of the pulse 0.5 and 1.5 mJ. For these energies the length of the coherence radiation reduces from 4 to 1 cm. The complicated appearance of the plot of the contrast versus relative delay is due to generation of a large number of longitudinal modes (up to 50),
their interference and the effect on the spectrum of an additional resonator with a low Q. The maximum of the contrast corresponding to a double length of the resonator as shown in Fig. 1, to the right from the break on the abscissa. The dotted line represents a computed dependence of the interference pattern contrast versus relative delay for the energy in the pulse 1.5 mJ. For the calculations the size of the laser resonator is chosen 50 cm long, the distance between the rear side of the rod and the front mirror is 12.5 cm.

The degree of the spatial coherence was measured by the Michelson interferometer using the technique advanced by Gerke R.R., Denisyuk Yu.N. and Lokshin V.I. /6/. One of the mirrors of the Michelson interferometer being replaced by an angular reflector, the wave from one arm of the interferometer is superimposed with the mirror-reflected wave emerging from the second arm. Waves emitted at the same angle interfere on the axis of the reflector. Measuring contrast of the interference pattern allows a degree of the spatial coherence to be determined. In Fig. 2 the module of the spatial coherence degree plotted versus distance from the axis of the interference pattern is given for three cases: 1 - energy of the pulse 1 mJ, spot intensity distribution is Gaussian; 2 - energy is 3 mJ, spot intensity is the same; 3 - energy 3.2 mJ, uniform spot intensity distribution. The dotted line shows the boundary of the image of the rear-side of the rod. The laser can easily be tuned to one of the transverse mode, including the mode 00, that enabled us to obtain a spatial coherence degree, practically equal 1. It is illustrated by curves 1 and 2 where the reduction of the spatial coherence degree up to 0.7 is observed at the periphery of the spot.

Thus, we may draw a conclusion that the laser radiation possesses high spatial energy-independent coherence and energy-dependent time coherence. The length of the time coherence at small energies is sufficient to create holograms of three-dimensional scenes. In case of high energies it is necessary that the relative delay of the reference and signal beams should be reduced to 1 cm. It can easily be accomplished in creating hologram of flat transparencies.

The Nd:YAG laser operating in the second harmonic with Q-modulation can successfully be used in holography, for example, in holographic data processing, in particular.

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Spatial coherence of the Nd:YAG laser
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