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RESOLUTION IMPROVEMENTS AND HOLOGRAPHY FOR NEUTRINO INTERACTIONS IN THE 15-FT BUBBLE CHAMBER

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1. Introduction

Standard three-view photos taken with the 15-ft. bubble chamber have provided spatial resolution, track quality and data handling capabilities which have been well matched to most of the physics applications of this detector over the past five years. The optics and photography design choices which were made[1] in order to produce these capabilities depended largely on limitations of focal depth, bubble size and bubble image contrast, which are known to be especially severe for bright-field conventional photography in deep chambers.[2,3] In practice the large chambers are typically operated with bubble sizes over 1 mm in diameter, several times the diffraction limit, for ease of film scanning and measuring. Smaller chambers with dark-field illumination can record bubbles grown well below the diffraction limit,[2] and with special optics can observe directly bubbles down to 10 microns diameter.[4]

This report is concerned with possibilities for auxiliary recording of very small bubbles in the 15-ft. chamber, including the application of bubble chamber holography, with more detailed analyses of vertices (for observing short-lived particles), and track ionization (for identifying fast particles). An order of magnitude improvement in bubble and track resolution is aimed at, oriented towards "second generation" neutrino experiments at present Fermilab energies as well as new experiments with the Tevatron. For direct study of cross sections, lifetimes and decay modes for charmed and other new flavored particles, and for studies of quark fragmentation and gluon contributions by analysis of the structure of individual neutrino events, desirable "yardsticks" for additional 15-ft. chamber capabilities considered here include a spatial resolution $\lesssim$ 15 microns, discrimination of $\pi/K/p$ by track ionization at ~15 GeV/c, combined with the use of ~15 tons of neon-hydrogen target.

2. Chamber Optics and Resolution

Mechanical and optical design features of the 15-ft. bubble chamber can be seen in Fig. 1. The cameras in Ports 4, 5, and 6 are regarded as "standard views" for observing and reconstructing neutrino interactions throughout the chamber volume. The cameras in Ports 2 and 3 are of special interest here for auxiliary, improved resolution, purposes.

Optical effects[1,2,3] limit both the smallest apparent bubble diameter d_{min} that may be resolved and the focal depth D over which the image quality is acceptable. In addition, bright-field illumination conditions with scotchlite, as in Fig. 1, also require for good image contrast that the bubbles are grown to a physical size d, comparable to the diffraction limited dimensions, d_{min}. Approximate values are shown in Table I and Fig. 2 for the limiting bubble diameter

$$d \simeq d_{min} \simeq \lambda\,(U/a)$$

and acceptable focal depth for conventional photography

$$D \simeq 4\,\lambda\,(U/a)^2$$

where λ is the illuminating wave-length, U is the object distance at the in-focus plane, and a is the diameter of the lens entrance pupil or aperture. Figure 2 also indicates "perfect focus" conditions expected with bubble chamber holography.[5]

Spatial resolution limits of tracks and their vertex intersections are largely determined by the bubble diameter, or track width. We take the limiting resolution, transverse to the particle direction, to be comparable to the measurement precision, which can be reduced to one-tenth the track width in many types of track chambers, i.e., $\sigma \sim \epsilon_m \sim d/10$. The existence of a secondary vertex due to decay of a fast particle with lifetime τ may then be sought if $c\tau \gtrsim 3\sigma$, or if $\tau \gtrsim 10^{-15}.d$ seconds, for a bubble diameter of d microns. For observing charmed particle decays with lifetimes down to 10^{-13} sec, precision measurement techniques and bubble diameters $d \lesssim 100$ microns are called for. As indicated in Fig. 2, this requires an order of magnitude smaller bubbles than observed under "standard" conditions for the 15-ft. chamber. With conventional photography the focal depth for recording such small bubbles would be reduced by two orders of magnitude, from $D \simeq 200$ cm to $D \simeq 4$ cm.

For hadronic interactions this may be acceptable, as in the high resolution streamer chamber technique[6] used in experiment E-490. (Shallow-focus optics have also been considered earlier for improved resolution in "hadron" cameras for the 15-ft. chamber[1] and for small bubbles in a TST for BEBC[7]). For neutrino physics, observation of charmed particle decays in auxiliary high resolution shallow focus views of the 15-ft. chamber would represent only a few percent of those produced in the full chamber volume, but would still be comparable in event rate with the use of nuclear emulsion stacks as in current Fermilab experiments E-531, E-553 and E-564.

The use of small resolved bubbles would be of special interest for particle identification by exploiting the relativistic rise of bubble density in heavy liquid chambers.[8,9] Figure 3 illustrates the potential for mass discrimination of fast particles in a high resolution neon-hydrogen chamber. The curves in Fig. 3, showing a relativistic rise up to 30%, are based on estimates of preferential contributions from neon K-shell and Auger electrons, as well as from experimental calibrations[9] carried out with a rich neon mixture in the Rutherford 150 cm bubble chamber. For the high resolution and high bubble density conditions listed in Table I, a potential ionization sensitivity of $\Delta I/I < 3\%$ is indicated for track lengths of one meter, to be compared with π/p differences $\simeq 16\%$ and π/K differences $\sim 10\%$ at $P \sim 15$ GeV/c in Fig. 3. Such potential use of track ionization within the detecting chamber appears to be similar to expectations for the pressurized Time Projection Chamber (TPC).[10]

If small bubbles can be realized for improved local track resolution, it can be expected that better overall chamber accuracy will be achieved for determining particle directions, momenta, invariant mass values and kinematic fitting. The accuracy $\varepsilon \simeq 300$ microns indicated[11] in track reconstruction of standard 15-ft. chamber photos may be expected to approach $\varepsilon \simeq 100$ microns (typical of smaller chambers) with short flash delays, as listed in Table I, with improved optical constants, and with continuing improvements in preventing the visible volume from experiencing thermal effects[3] which degrade the optical image and track qualities.

3. Holography

Development of holographic techniques for bubble chambers was investigated extensively about 10 years ago, chiefly by the Optics Group at Imperial College[5] and also by the Institute of Optics, University of Rochester.[12] The added complexity of holography did not make these techniques appear competetive with conventional photography for recording the relatively large diameter bubbles ($\gtrsim 500$ μm) considered satisfactory at that time for particle physics. (Application of holography was found for other "particle" studies - the size distribution of fog droplets and aerosol particles with diameters in the range 4 to 200 microns.[12])

Figure 3 shows essential features of the optical design which evolved at Imperial College for holography in deep bubble chambers.[5] The film records interference patterns corresponding to bubble images at various depths of focus, forming an image hologram of the chamber and its contents. The hologram is reconstructed by illuminating the developed film with a reference beam similar to that used in making the image. Viewing of re-formed bubbles and track segments in focus at various depths could be done with a zoom system, in which the track images can also be projected (and digitized) by television or other light sensing devices, in much the same way that tracks at different depths in nuclear emulsion can be examined, projected and digitized under microscopy. Camera lens relative apertures near f/3 were found suitable in track holograms over several meters depth, in simulation studies using glass beads (~500 micron diameter) in liquids.

For application of these holographic techniques to small bubbles in the 15-ft. chamber, the principal areas requiring further development would appear to be in the fields of suitable high powered liquid dye lasers, (tuned to wavelengths below the cut-off filter in the "standard" photos) and in image processing to make best use of bubble constrast,[13] as well as profile, in the presence of image noise and speckle.[5,14]

4. Conclusions

Recording of small bubbles in the 15-ft. bubble chamber would allow unique improvements in resolution capabilities for neutrino interactions, and appears to be technically feasible.

Four areas of technical studies and improvements are indicated, for early applications:

1. Adjustment of the present optics and flash timing in Views 2 and 3 viewing small bubbles and neutrino interactions near the top of the chamber, as in the "medium" resolution conditions column in Table I.

2. Design and installation of special wide-aperture camera lenses for shallow focus high resolution photography (third column of Table I). Preferably, these lenses should fit into the existing fish-eye window assemblies, not require major changes to the camera assemblies, and allow provision for later use with holography as in Fig. 4.
3. Development of precision film viewing and image processing systems for vertex resolution and track ionization with small bubble images on high resolution (holographic) film.
4. Design and implementation of holographic optics in the auxiliary views, for high resolution studies throughout the full volume of the 15-ft. chamber.

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TABLE I

OPTICS AND RESOLUTION CAPABILITY ESTIMATES FOR THE 15-FT. BUBBLE CHAMBER

Resolution Condition -	"Standard"	"Medium"	"High"
Object distance U - cm	200	75	200
Entrance pupil diameter a - mm	2.2	3	15
Focal depth $D = U'-U \simeq \lambda(U/a)^2$ - cm	200	15	4
Resolved bubble diameter d_{min} - μm	550	150	75
Lens focal length f - mm	37	37	37-80
Aperture stop N $a = f/N$	f/17	f/12	f/2.6-f/5.3
Resolved bubble diameter on film (Airy disc) $d' \simeq \lambda(f/a)$ - μm	10	6	1-2
Magnification $M \simeq U/f$	55	20	55-25
Flash delay - msec	~ 7	~ 1	~ 1
Minimum ionization I_{min} - bubbles/cm	~ 7	~10	$\gtrsim$ 25

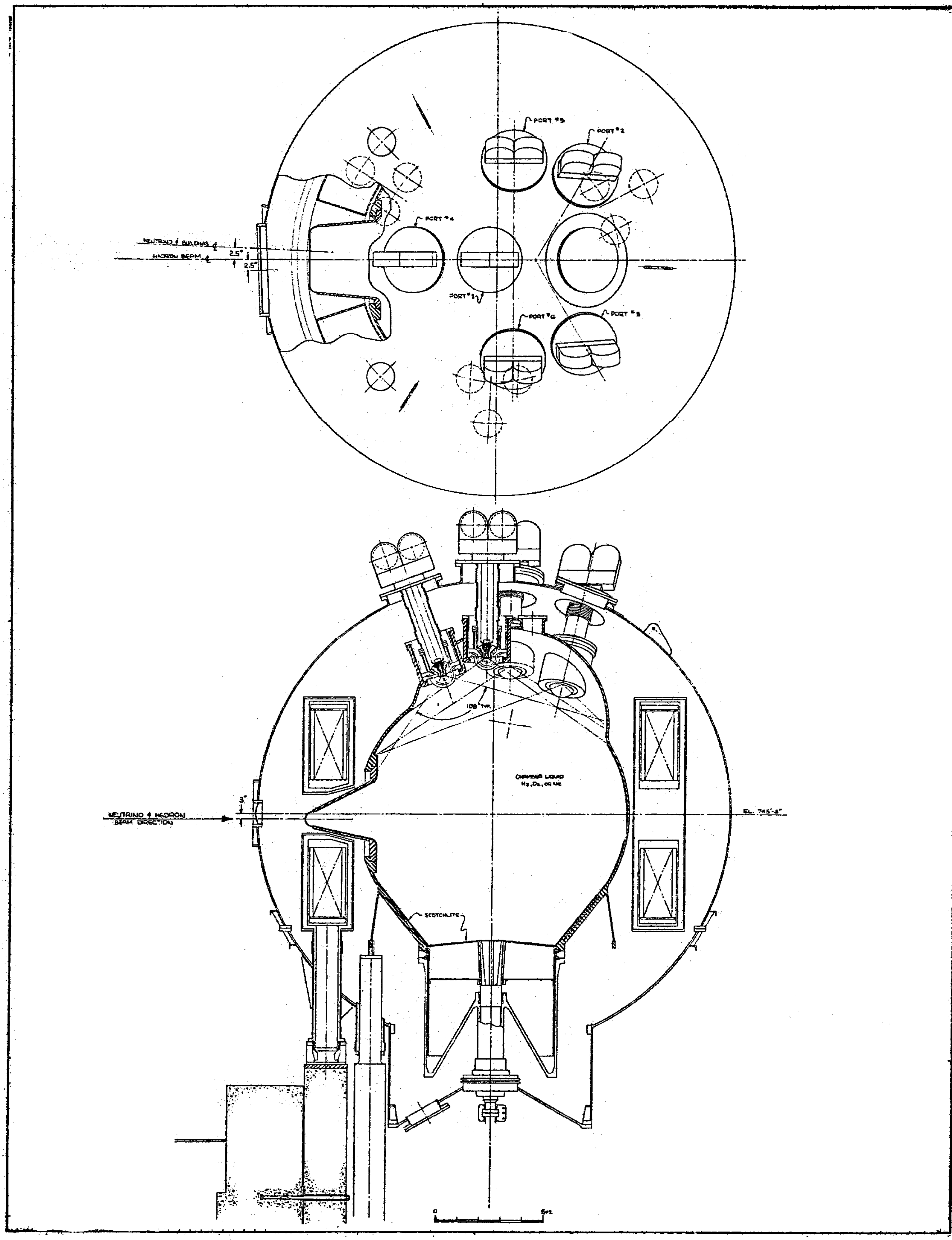

Fig. 1. General assembly views of the 15-ft bubble chamber.

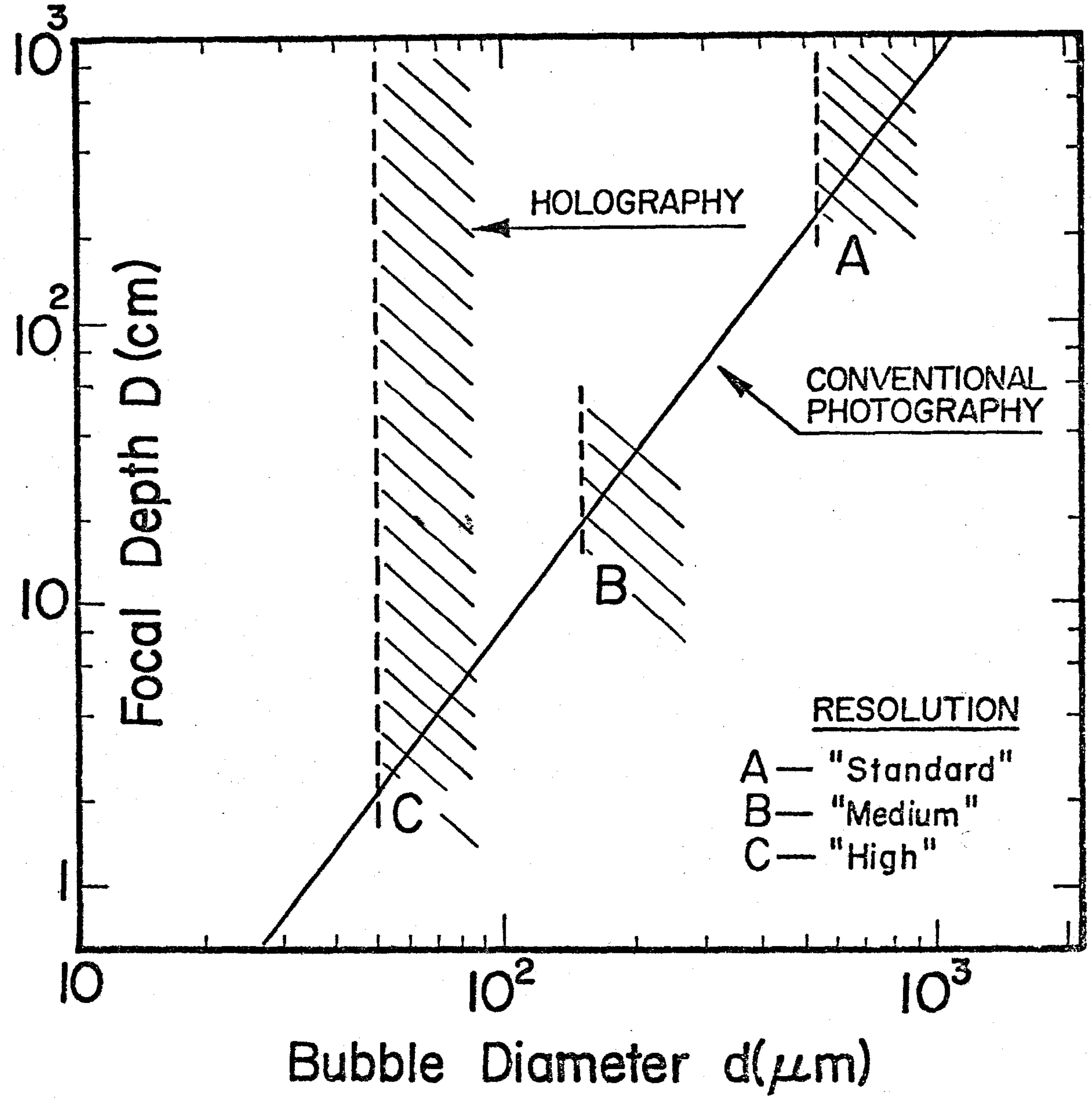

Fig. 2. Approximate values of focal depth and minimum bubble size for various conditions of track resolution in the 15-ft chamber.

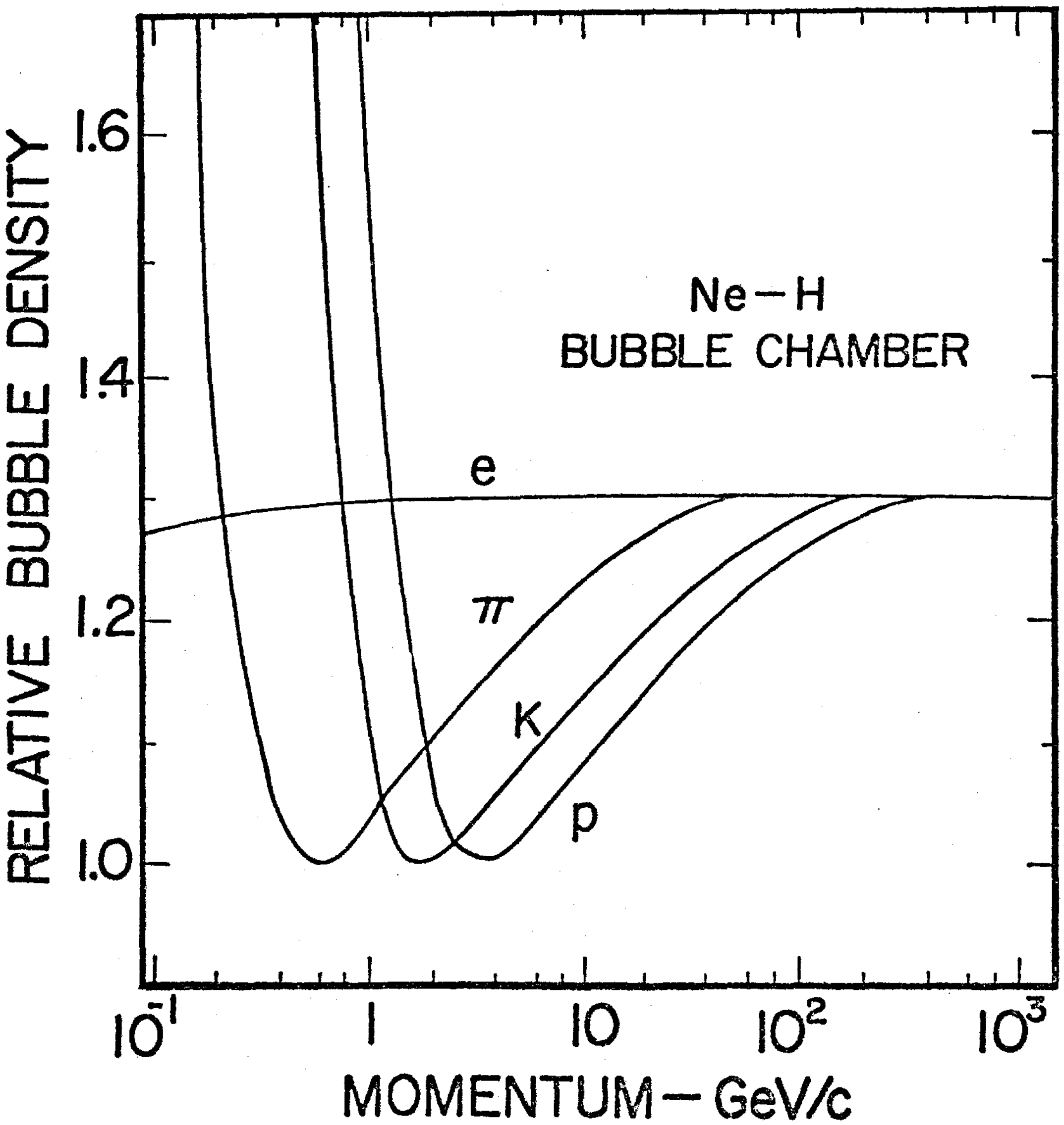

Fig. 3. Approximate dependence of the relative bubble density in a high resolution neon-hydrogen bubble chamber.

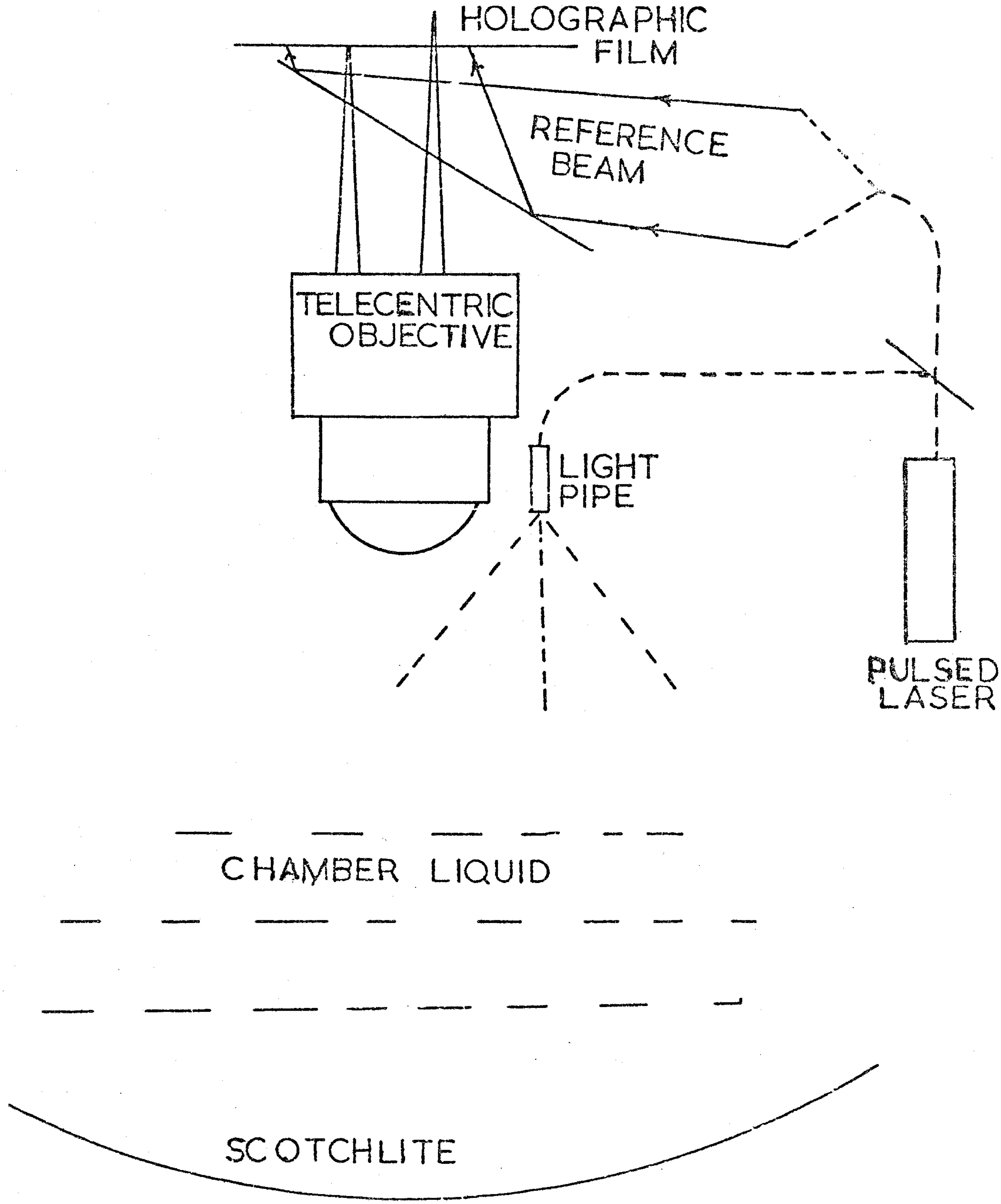

Fig. 4. Diagrammatic representation of optical design for holography in a deep bubble chamber (from Welford[5]).