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Track Sensitive Targets, Hybrid- and Rapid Cycling Chambers

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1. INTRODUCTION

This contribution reports on the development and on the application of particular techniques in the bubble chamber field. It starts with Track Sensitive Targets (TST) which combine the advantages of hydrogen/deuterium as target liquid with those of a heavy liquid for efficient gamma conversion. In this way, interactions of beam particles occur exclusively with free protons in hydrogen or quasi-free neutrons in deuterium, and neutral pions, which form 1/3 of the produced secondaries, are detected via the conversion of their decay gammas into electron-positron pairs in the neon hydrogen mixture. Both liquids are separated by a transparent box (TST) where the flexible walls transmit the pressure reductions of the bubble chamber into the pure liquid hydrogen or deuterium in order to obtain track sensitivity simultaneously inside the TST and in the surrounding neon-hydrogen filling of the bubble chamber.

The second part continues with visual Charm detectors. Production cross-sections and decay properties of charmed particles required bubble chambers, which were in many respects different from conventional ones. They must be operated as track sensitive targets of a hybrid system which provided (NA27) momentum measurements, particles identification, gamma- and neutron detection. To cope with small Charm cross-sections and their short decay lengths of a few millimetres asked for rapid cycling expansions and high optics resolution.

2. TRACK SENSITIVE TARGETS

2.1. The Proposal and Basic Data

Around thirty years ago the bubble chamber groups at Argonne, Broohaven, CERN and Dubna studied designs of giant H_2/D_2 -chambers. The aim was to do neutrino physics

Figure 1. Vapour pressures of Ne- H_2 mixtures.

and to achieve four-or three constraint fits with hadron-or neutrino interactions, which implied in particular the detection of gammas arising from neutral pion decays. The proposed solutions were heavy metal plates conveniently arranged to photograph the gaps in between them and optimized for gamma conversion efficiency and momentum resolution of the outgoing electron-positron pairs. Obvious drawbacks were the obscuration of optics, hydrogen/deuterium turbulences and considerable gamma momentum errors.

In 1965 an article on "Liquid Phase Separation and Liquid-Vapor Equilibrium in the system Neon-Hydrogen" was published [1] by W. B. Streett and C. H. Jones. Apart from a general interest on this binary cryogenic system, the authors mention a possible application of neon-hydrogen fillings in bubble chambers proposed and tested [2,3] by R. P. Shutt and his group.

Figure 2. Area of phase-separation.

By translating the pressure-composite data of that paper into vapour pressure curves (fig. 1) the author of these proceedings realized, that simultaneous track sensitivity of neon-hydrogen with pure hydrogen or deuterium could be achieved under selected pressure-temperature conditions and proposed [4] that a "beam target filled with pure hydrogen or deuterium should be placed in the big chamber which is filled with a hydrogen-neon mixture". And subsequently, the basic topic of the TST-technique is described: "a target construction is proposed, which follows automatically the pressure change of the surrounding hydrogen-neon mixture".

During the next years the data of Streett and Jones, which already contained the area of phase separation (fig. 2), where the mixture separates into a heavy (neon rich) and on top of it, a light component, were supplemented by measurements of D. Güsewell, F. Schmeissner,

Figure 3. First TST for the Desy test run.

and J. Schmid on densities and sound velocities [5]. The refractive indices of neon-hydrogen mixtures were measured at RHEL by R. Newport [6] with the interesting result that the refractive index curves of pure neon, pure hydrogen and the neon-hydrogen mixtures crossed at 29.2 K with 1.088 refractive index. Finally, all relevant data on neon-hydrogen mixture have been compiled in 1974 [7].

2.2. Test Runs at DESY

The most difficult task was to find a bubble chamber with a crew ready to take the risk of operating a TST for the first time. In 1967, the DESY-management [the author is indebted to the late M. Teucher for his support] agreed to a technical run with a TST in the Desy-85 cm chamber [8]. The target (fig. 3) was a tambourine like container of 1.3 l volume with flat Mylar walls of 0.2 mm thickness glued with araldite on an aluminium ring. The neon content of the surrounding liquid was increased

Figure 4. First simultaneous tracks in pure H_2 and in the $Ne-H_2$ -mixture.

Figure 5. Deuterium-TST mounted in the 85 cm DESY bubble chamber.

stepwise up to 14 mole % (fig. 4). This target was operated for 40000 expansions at a rate of 0.5 s^{-1} until one of the Mylar foils tore away from the aluminium.

Encouraged by this first test we started in 1968 again at Desy a run with a deuterium filled TST [9]. Following the original design, the target was again integrated as a passive element into the bubble chamber, this time filled with 95 to 95.6 mole % neon-hydrogen. The target (fig. 5) was a cylindrical box of 30 cm diameter and 10 cm height which contained 7 l of liquid deuterium. Its mechanical stability was ensured by a stainless steel frame covered at its flat walls and also at its cylindrical part with Mylar. A table tennis ball inside the target was matched with its overall density to that of liquid deuterium. A contamination of 1 mole % neon produced enough buoyancy to lift it from bottom to the top. Track sensitivity was achieved throughout the above mixture range (fig. 6). The target failed after 18000 expansions due to Mylar rupture as in the preceding exposure.

Figure 6. First simultaneous tracks in pure D_2 and in the $Ne-H_2$ -mixture.

2.3. Physics Runs at RHEL

Following the first successful tests with TST's of the CERN-DESY collaboration, it was decided to develop also a TST-facility for the 1.5 m British National Chamber at the Rutherford High Energy Laboratory (RHEL). In this cryogenic chamber the gas driven liquid expansions are directed vertical whilst the optical axes and the magnetic field directions are horizontal and normal to the particle beam. The beam is wholly contained inside the TST, which forms a vertical slice through the centre of the chamber (fig. 7). Beam spread and curvature produced by the magnetic field stay in the target plane and all beam particle interactions occur in hydrogen whilst a large solid angle is presented for gamma conversion by the neon-hydrogen fill of the bubble chamber. Again, no separate expansion mechanism is provided for the TST. In contrast to the Desy-runs, the target consists now of Plexiglas (Perspex) with a heat exchanger loop at its top, and the pressure variations in the neon-hydrogen of the chamber were again directly transmitted via its flexible walls to the hydrogen contained inside the TST.

Figure 7. E. Amaldi (left) and P. Williams looking at a TST mounted as a vertical slice through the 1.5 m chamber in RHEL.

Table 1. Physics pictures taken at RHEL with the 1.5 m chamber-TST-system.

Nb of pictures		65 K	220 K	839 K	423 K	94 K
beam	Gev/c	4 (π^+)	4 (π^+) 2 ($\bar{p}$)	4 (π^+)	4 (π^+)	4 (π^+)
Molar fraction Ne		0.45	0.73	0.77	0.80	0.82
mixture temperature	K	29.3	29.6	29.6	29.6	29.6
target temperature	K	29.3	29.4	29.3	29.2	28.9
static pressure	bar	7.9	8.3	8.3	8.1	8.1
expanded pressure	bar	5.1	5.5	5.2	5.1	4.8
bubble growth time	ms	2.8	2.8	2.8	2.8	2.8

TOTAL Nb of pictures : 1.641 K

Time periods : November 1971 ; July-December 1972

The wall deflections necessary to produce the 1 % change of the target volume, (1350 mm long, 280 mm high, 50 mm deep) required for suitable track sensitivity, were of the order of 0.5 mm. The target shape was monitored by a pattern of four strain gauges glued to its walls. Target runs in 1969/70 were performed with only 2 mm wall thicknesses, which caused destructive plexiglas-oscillations. Also, to

avoid phase separation of the neon-hydrogen mixture (fig. 2), required an operating regime at temperatures well above 29 K (table 1) which asked for static chamber pressures above 8 bars. This led to deformations of the chamber top plate with its 80 inlets for the pipes of the gas expansion system which deteriorated severely the vacuum around the chamber body.

Figure 8. Four gammas converted in a 80 mole % Ne-H₂ mixture (fat tracks) pointing at a beam interaction (faint tracks) with hydrogen inside the TST.

Finally, after having increased the target wall thickness to 6 mm and strengthened the top plate structure, the physics programme started in November 1971 [10, 11, 12]. The neon concentration in the mixture was steadily raised (table 1) and 1.44 million pictures have been taken during November 71 and from July to December 1972. In operation, the system was extremely stable, the mixture remained homogeneous and track quality in the TST and chamber (fig. 8) was constant. High operating efficiencies were achieved, for example the 423 thousand pictures (table 1) were taken in 17 days with an overall efficiency for accelerator, beam and chamber of 79 % [13].

2.4. US-efforts for TST applications

In 1964, M. Goldhaber from BNL suggested the use of neon-hydrogen mixtures in cryogenic bubble chambers. This suggestion was confirmed by the measured data of Streett and Jones [1] and experiments in the 20 inch [2,3]- and 80 inch- bubble [14] chamber at BNL showed encouraging working conditions for neon-hydrogen mixtures.

Figure 9. A BNL- target of cylindrical shape with differential expansion system.

In spite of the successful TST-tests at Desy and the physics runs at RHEL the design of TST-systems at BNL and at LRL/SLAC followed a different strategy. The aim was to achieve different pressure conditions between target and chamber via bellow driven differential expansion systems in the TST. This asked of course for cylindrical target structures. A BNL-construction is shown in fig. 9. In contrast to a TST with flat walls a cylindrical shaped one provides considerable track displacements which are not parallel but change direction depending on the viewing angle of the camera and the track azimuth angle. Moreover, large angular incidences of the light rays provokes high reflectivity, which shadows the target region and leaves only a small zone along the middle part of acceptable optics quality (fig. 10).

In 1970 a TST programme started at Argonne Nat. Lab. as a joint effort between ANL, RHEL, CERN and Tohoku University, Japan. Flat targets of 200 cm length, 36 cm width and 10 cm height were built at CERN to be installed in the Argonne 12-foot chamber, which provided in October 1969 the first particle tracks of the designed giant

Figure 10. Cylindrical TST operated in a hydrogen filled chamber.

Figure 11. Flat TST in the neon-hydrogen filled 12 foot ANL-chamber. Three gammas point at the hydrogen interaction inside the target. Some dirt on top of TST obscured its optics.

chambers. It was mounted as an horizontal slice supported at each corner by spring-loaded stainless steel bars and contained a heat exchanger running around its upper edges (fig. 11). Most of the instrumentation like strain gauges, position transducers and gas sampling and analysis equipment was set-up by RHEL. The neon was provided by Tohoku University. TST-runs were performed in 1973/1974.

2.5. Neutrino Target in the Big European Bubble Chamber (BEBC)

In 1975, we [H. Ancey, G. Geydet, R. Girardot, H. Leutz, J. Tischhauser and M. Thevenon at CERN] changed the basic TST-material from Plexiglas to a thermoplastic Polycarbonate with trade name Lexan. This plastic material offers excellent impact and tensile strength together with 20 % elongation at cryogenic temperatures and therefore resisted the severe shocks caused to the walls of the large neutrino target by the expansion accelerations of the surrounding neon-hydrogen. To realize a clean target with smooth surfaces and edges, all parts had to be glued carefully together.

With solvent (methylene chloride) cementing, at 70 bars pressure, rather than with adhesive bondings, we achieved vacuum tight joints of high structural integrity. To avoid light absorption, we did not use normal Lexan with its blueish tint, but ordered a special type [SL 3000; General Electric Comp., Mount Vernon, Indiana, USA] produced under stringent precautions against dirt contamination. Then, at another place [Westlake Plastics Comp. Lenni, Pennsylvania, USA], three (for the side walls) or four (for top-and bottom plates) 1/4 inch thick sheets of this raw material were sandwiched between two highly polished chromium plates and by a heating procedure, patented as "press-polishing", amalgamated to 3/4 inch or 1 inch thick plates. This procedure resulted in optical grade Lexan plates of high light transmittance. All metallic parts of the TST such as the filling valve, the vapour pressure bulb and the heat exchanger in and outlet, were vacuum sealed to the target body by a shrinking technique: the steel parts were cooled to liquid nitrogen temperature and fitted into appropriately dimensioned borings in the Lexan structure.

After these preparations, a neutrino target 2.4 m long, 1.4 m wide, and 1.0 m deep with

Figure 12. Large neutrino TST mounted inside BEBC at CERN. The light loss induced by the eight LEXAN interfaces covered with antireflection coatings is still visible, but was reduced by filling TST and chamber and by masks in front of the cameras.

3.36 m³ volume was constructed in 1977. During spring 1978, it was mounted into the 30 m³ Big European Bubble Chamber at CERN. Fig. 12 shows the TST inside the empty chamber. The beam entrance wall and 0.6 m of the bottom plate were covered with Scotch-lite, since in this region no tracks in the surrounding mixture were expected. Although the Lexan plates were covered with anti-reflection coatings, the light loss induced by eight interfaces is still visible, but has been reduced by the refractive index of the chamber-and TST liquids and equalized by camera masks (film negatives) later on, as can be seen in fig. 13. It shows a high multiplicity neutrino interaction inside the hydrogen liquid of the TST and six electron-positron pairs pointing at it, which indicate the production of three neutral pions. The TST was mounted at its four vertical edges on steel bars fixed at the bottom of the chamber body. Carefully loaded copper-beryllium springs damped its vertical

movements during the expansion cycles.

Physics exposures started in April 1978 with 76 mole % neon in the mixture. Table 2 lists the experiments completed until end of July 1978. More than one million pictures have been taken during 3.5 months, 85 % of them in the double expansion mode, i.e. the hadrons were injected at the beginning and the neutrinos at the end of the 12 s SPS-flat top. Fig. 14 shows one view of a $\Delta S = -\Delta Q$ neutrino event leading to a completely reconstructed production and decay chain (unique 3C-fit) of a positive Sigma charm particle [15]. The proton was stopped and the gamma pair of the neutral pion was converted in the mixture. Both positive pions interacted with neon, in this way excluding kaons. The negative muon was identified by the External Muon Identifier (EMI) surrounding BEBC outside its magnetic iron shield.

To conclude this chapter on TST's, I should also mention some efforts in Serpukhov. After

Figure 13. High multiplicity neutrino event in the hydrogen of the TST (faint tracks) and six electron-positron pairs from the decays of three neutral pions in the Ne-H₂ mixture (fat tracks) pointing at it.

Table 2

Experiments completed with the large neutrino TST in BEBC. 61% of all BEBC pictures have been taken with Ne-H₂ (44%) and TST (17%).

Expt	Interaction	Proposal	Nb of publ.	Nb of K-pictures
WA 24	νp	neutrino	7	315.89
		interact. in H ₂		272.06
WA 30	νp	antineutrino	3	243.55
	70 GeV $\Pi^- p$	direct e-production		190.04
WA 31	70 $\bar{p} p$	prompt lepton production	2	

867.18 K-pictures taken in double pulse mode. Total 1 021.54

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FIRST OBSERVATION OF THE PRODUCTION AND DECAY OF THE Σ_c^+

unique 3C-fit to: $\Delta S = -\Delta Q$

Figure 14. First observation of the production and decay of a completely reconstructed Σ_c^+ . Note that the mass determined in 1980 is still close to the average of the 1992 Particle Data Book.

contacts with CERN, a flat shaped TST was built by russian and french engineers and mounted in "MIRABELLE" a big horizontal cylinder body of 4 m length built in Saclay and delivered to Protvino. Another TST was inserted recently in the 2 m chamber "LUDMILLA", a copy of the old 72 inch chamber at Berkeley. In contrast to other TST's it was used to save deuterium by filling it with this liquid and surrounding it with liquid hydrogen. To provide tracks simultaneously in both media the TST was kept at a temperature 3.8 K higher. 300 thousand pictures were taken in an anti-deuteron beam of 12 GeV/c.

3. CHAMBERS FOR CHARMS DETECTION

[The SLAC-HYBRID system will be reported as a short communication]

3.1. Design parameters

The expected charm life times range between 0.1 ps and 1 ps which span decay lengths from 1.2 mm to 12 mm at the CERN SPS and from 2.4 mm to 24 mm at the Fermilab Tevatron. These short decay distances require hit (bubble) densities of more than 8 mm^{-1} to distinguish clearly charged from neutral charm particles. The target should contain no neutrons to allow for unambiguous discrimination between charm decays (even prongs for neutral ones, odd prongs for charged ones) and secondary interactions (even prongs for charged and odd ones for neutral primaries). Moreover, to measure clearly charm production cross-sections requires material of atomic number $A=1$ to avoid its still unknown exponent α , ranging between 0.7 and 1. Finally, the impact parameters of the charm-decay products equal roughly the c -length, and therefore a two track resolution of about $30 \mu\text{m}$ is required.

Following these requirements, the detector specifications ask for liquid hydrogen as target material, and a bubble chamber as visual detector. With 15 % duty cycle and 60 % accelerator efficiency this chamber should provide 10 % interaction probability per expansion cycle at an expansion rate of 30 s^{-1} to aim at about 3 charm events per day. Because of the $2 \mu\text{m}$ grain size of the film, the optics magnification should be close to unity, which means that chamber length and frame length of the film should be equal. A camera rate of 15 s^{-1} allows for 10 cm frame length, which defines the chamber length and in turn 15 tracks per picture.

3.2. The hydrogen filled Lexan Bubble Chamber (LEBC)

To realize these specifications asked for a chamber cycling at 30 Hz and for rather

sophisticated optics. To avoid any dynamic heat load due to parasitic boiling we [H. Ancey, G. Geydet, R. Girardot, H. Leutz, J. Tischhauser and M. Thevenon at CERN] constructed the chamber from the thermoplastic polycarbonate LEXAN as we did already for the large neutrino TST. All parts were glued together without any seals or weldings to achieve smooth edges and low thermal conductivity everywhere. As fig. 15 shows, the Lexan Bubble Chamber (LEBC) consisted of two main regions. A rectangular one with a 12 cm long and 5 cm high visible region. The heat exchanger on top provided at 29.3 K track sensitivity with 10 mm^{-1} bubble density.

Figure 15. The LEXAN Bubble Chamber LEBC with two windows for straight through photography at its upper track sensitive part. The lower invisible part contains the Lexan expansion membrane and is subcooled to 24 K to avoid any dynamic heat load. The expansion piston acts outside the membrane with 0.5 mm stroke.

The circular invisible part at the chamber bottom contained the 3 mm thick LEXAN expansion membrane. Its 30 cm diameter provided with only 0.5 mm piston stroke the required track sensitivity in the visible region. The adiabatic pressure cycles were generated by a forced hydrolic servo-system [designed and constructed by : J. L. Benichou, A. Herve, J. Pothier and G. Waurick at CERN] with its piston acting outside the LEXAN membrane. The piston surface of 25 cm diameter contained a heat exchanger which subcooled the invisible part of the chamber to 24 K, in this way avoiding any spurious boiling within the expansion region. During all LEBC exposures, the expansion system cycled around 70 million times and performed outstandingly well.

The chamber body and all cold components (fig. 15) were installed inside a common cylindric vacuum tank of 0.8 m diameter and 1.4 m height. LEBC was cooled by forced circulation of two phase hydrogen [The refrigeration system was designed by G. Passardi at CERN]. Liquid hydrogen was continuously transferred over 20 m from a pressurized storage Dewar into a 20 l container inside the vacuum tank. The static pressure of the chamber liquid was measured with a pressure gauge and kept automatically constant via corresponding changes of the piston rest-position : 0.1 mm piston position change corresponded to 15 mb. All metallic parts were again shrunk into the top of the chamber like at the large neutrino TST.

3.3. The heavy Liquid filled Chambers BIBC and HOBC

Since the design-and operating conditions of heavy liquid (Freon, Propane)-chambers are much less severe as for hydrogen ones, these groups decided to construct small chambers which could run close to ambient temperature. In this way they gave up the easy discrimination between charm decays and secondary interactions and the unambiguous determination of charm production cross-sections.

When charm physics with bubble chambers started in 1979, the Bern Infinitesimal Bubble Chamber (BIBC) existed already. It became famous with its first holographic pictures of bubble chamber tracks [16]. Its visible volume is cylindrical with 65 mm diameter and 35 mm depth between the two optical windows of 15 mm thick BK-7glas (fig. 16). Pressure cycles of 8 Hertz were transmitted via a rubber diaphragm from a pneumatic expansion system. Temperature stabilization is provided by a thermostat-circulator, which pumped water through passage ways in the chamber body.

HOBC was a 2 l heavy liquid bubble chamber (fig. 17) with two optics windows for in-line holography [17]. The visible chamber volume ($5 \times 6 \times 11 \text{ cm}^3$) was joined via a conical section to the 200 mm diameter stainless steel bellows with the expansion piston. The active liquid was separated from the piston and the expansion bellows by a 1.5 mm thick VOLKOLAN rubber membrane. The thermal control of the chamber was achieved by two

Figure 16. The Bern Infinitesimal Bubble Chamber BIBC.

Figure 17. Stainless Steel Chamber body of the Holographic Bubble Chamber HOBC.

water loops in the chamber body and one loop in the piston. The whole assembly is surrounded by an aluminium tank heated to the same temperature as the chamber body.

3.4. Optical Layouts for Photography of Small Bubbles

The heavy liquid chamber HOBC recorded all pictures of its physics runs with in-line holography (fig. 18) where an expanded laser beam provides colinear object -and reference rays which interfere at the film plane. Each bubble produces its proper Fraunhofer diffraction patterns (Fresnel zones). The main difference to conventional optics is in the depth of field, which is 7500 times larger with holographic than with classical recording, if we assume 100 mm coherence length for laser light of 500 nm wavelength. The optical resolution of a bubble with diameter ϕ amounts in the classical case to:

Figure 18. In-line holographic recording arrangement.

$$\phi = 1.22 \lambda / \alpha \quad (1)$$

and for holographic recording to :

$$\phi = 1.22 \Delta X \quad (2)$$

with λ meaning the wavelength, α the light diffraction angle, ΔX the distance between the just resolved outer fringes, and $3.83/\pi = 1.22$ the circular aperture of the principle diffraction maximum [18].

This has consequences for holographic recording of bubble tracks. In a bubble chamber heat is transported by turbulent convection of small eddies since thermal conduction of liquid hydrogen or freon is much too small to establish the temperature uniformity required for stable track sensitivity throughout the photographed volume. Taking LEBC as an example the radiative heat incident through its optics windows was about 2 W, whereas the dynamic heat load can be neglected. Therefore, the eddies of about 1 mm size transport a vertical heat flux H of 0.04 W cm^{-2} up and a corresponding cold flux from the top heat exchanger down. Their refractive indices n are different from the average :

Figure 19. Track hologram recorded in LEBC with $30 \mu\text{m}$ bubble diameter.

$\Delta n = 5 \times 10^{-3} \text{ K}^{-1}$. This causes light ray displacements [19] of

$$\Delta X = 45.6 H^{7/8} L^{3/2} = 30 \mu\text{m}$$

if the heat flux H is taken in W cm^{-2} and the path length L in the turbulent hydrogen in cm. In holography, this constitutes according to relation (2) a resolution limit for $30 \mu\text{m}$ bubbles. In heavy liquids, the radiative heat load is replaced by the dynamic one. Since these chambers are operated close to ambient temperature (HOBC at 53°C) their heat flux is smaller and the resolution limit is in the range of $10 \mu\text{m}$ to $15 \mu\text{m}$.

Another restriction for holography is the obscuration of holograms caused by the amount of fringe patterns produced by the track bubbles. Therefore, HOBC worked with an average of 70 beam particles [21] in order to not exceed 1% obscuration. In fact this represents the real limit for the number of recorded tracks rather than the depth of field. The following figures show the recorded track holograms taken in LEBC (fig. 19) with $30 \mu\text{m}$ bubble diameter, in BIBC (fig. 20) with $13 \mu\text{m}$, and in HOBC (fig. 21) with $12 \mu\text{m}$ diameter.

Figure 20. Track hologram recorded in BIBC with 13 μm bubble diameter.

The holographic efforts with LEBC were regarded inadequate and it was decided to apply classical optics. Fig. 22 shows the basic scheme. The two light sources consisted of the roughed ends of 1 mm diameter optical fibres

fed by a pulsed dye laser. Condensor lenses illuminated uniformly the visible volume of the chamber and each of the two stereoscopic light beams was focussed onto the aperture of its proper camera objective, which imaged the

Figure 21. Track hologram recorded in HOBC with 12 μm bubble diameter.

Figure 22. Optics layout for LEBC.

diffracted light of the bubbles onto the film plane. With the objective lens aperture we adapted the principle diffraction maximum to the bubble diameter defined by the chosen flash-delay. In this way we used diffracted light rather than the refracted one normally applied in bubble chambers. This scheme rendered classical photography of bubbles below $20\text{ }\mu\text{m}$ diameter at all possible since the diffractively scattered intensity was about 20 times stronger than the refractive one. Fig. 23 shows a 14 prong event photographed in bright field with bubble diameters of $15\text{ }\mu\text{m}$. The central tracks of this event are shown on an HPD-print (fig. 24) magnified in Y and compressed in X at a ratio of 650. The turbulence motion of liquid hydrogen can be seen from the displacements of the bubble-centres, which do not influence the resolution as with holographic recording.

Figure 23. Bright field photography of a 14 prong event in LEBC.

Figure 24. Central tracks of the 14 prong event recorded with the Strasbourg HPD.

3.5. Results of Charm Exposures

In the CERN NA18-experiment [22], BIBC filled with freon (C_3F_8) has been exposed to a 340 GeV/c π -beam as a vertex detector in front of the 2 m-MPI (München)-streamer chamber as a spectrometer. 155000 pictures were taken with classical optics, at 30 mm⁻¹ bubble density and with 30 μ m bubble diameter. From 94200 inelastic interactions 768 events could be reconstructed in both chambers separately, and for 456 events all tracks could be matched between BIBC and the streamer chamber. After cleaning them from strange particles, 29 candidates remained and 21 were accepted as charm decays which satisfied a kinematical three constraint fit: $9 D^0 \bar{D}^0$, $7 D^\pm$ and $5 F^\pm$ with an expected background of 1.4, 2.2, and 2.4 events respectively.

The first holographic bubble chamber experiment (NA25) [21] was realized with HOBC at CERN in π beams of 360 GeV/c and 200 GeV/c momentum. The freon (C_3F_8) - filled chamber was positioned in front of a muon detector composed of a 2 m iron dump with a tungsten core followed by a sandwich of iron plates, multi-wire-proportional chambers

Figure 25. The tambourine shaped predecessor of the final LEBC-version (fig. 15) used in the NA 13- and NA16- experiments.

and scintillator counter hodoscopes. In this way semileptonic charm decays into forward muons were selected.

At 10 Hz cycling rate and 10 mm⁻¹ bubble density HOBC resolved 12 μ m diameter bubbles. Each of the 40000 holograms recorded contained typically 70 beam tracks with five interactions. 6325 of them were retained for final analysis. Most of the topological background arose from gamma conversions (280 mm radiation length in C_3F_8), strange particle decays and misidentified secondary interactions. 298 candidates survived these background cuts, containing 146 1-prongs, 61 2-prongs, 31 3-prongs, 3 4-prongs and 57 candidates of unknown charge. Assuming a linear dependence ($\alpha=1$) of the charm cross-section on the atomic number A , the production cross-section of charm pairs per nucleon was found to be $(23.3^{+10}_{-7.7}) \mu$ b and $(3.6^{+2.3}_{-1.7}) \mu$ b at 360 GeV/c and 200 GeV/c respectively.

Data taking with hydrogen filled LEBC chambers comprises three experiments (NA13, NA16, NA27) at the CERN SPS and one (E743) at the Fermilab Tevatron. NA13 was a 2.5 events/ μ b exposure in June/July 1979 with a

Table 3

Beam exposures with LEBC-chambers at the CERN-SPS and at the Fermilab Tevatron.

Experiment	Triggered pictures $\times 10^6$	Chamber expansions $\times 10^6$	Sensitivity Evts / μb	Identified Charm decay	pairs %
NA 13 $\pi^- p$	0.11	1	2.5	15	
NA 16 $\pi^- p$	0.35		7.8		
$p p$	0.50	20	7.3	103	72
NA 27 $\pi^- p$	0.85	10	15.8	183	80.3
$p p$	2.22	25	38.5	557 *	83.7
E 743 $p p$	1.2	15	12.0	56 **	
Total	5.23	70	83.9	914	

* 7C5 134C3 61C1 ; 57 unclear topology but clear charm signature

2V6 54V4 166V2 ; 75 no clear charm signature but paired with a clear charm

** Only C3 (43) and V4 (13) topologies

20 cm diameter tambourine shaped LEXAN chamber of 4 cm depth (fig. 25) [24]. Tracks were photographed in bright field through a Lexan window and with retrodirective scotchlite glued to the expansion membrane at the rear of the chamber. A total of 110000 pictures containing 48000 events were taken (see table 3). Since there was no spectrometer and no magnetic field, only topological evidence for 12 charm pairs and in addition for 6 charged 3-prong decays could be claimed.

With the same chamber, but now positioned as a vertex detector in front of the 1980 still incomplete European Hybrid Spectrometer (EHS) [25] two beam exposures were performed (see table 3) at CERN. This experiment is known as NA16 [26,27]. Amongst the 103 identified charm decays was at the beginning of the NA16-run a fully reconstructed $D^0 \bar{D}^0$ pair with two proper life times [28] making a striking impact on the D^0 -lifetime determined before (fig. 26).

Figure 26. Chronological plot of D^0 -lifetimes.

Figure 27. Layout of the European Hybrid Spectrometer (EHS).

In 1981, LEBC has been built in its final version as described before (fig. 15), the main improvement being now its two windows to achieve high optics resolution. It served again as a visual target with minimal topological ambiguities in front of the now completed EHS [38]. This experiment performed two big exposures with 360 GeV/c π - and 400 GeV/c p-beam and is known as NA27 (table 3) [34,39].

EHS (fig. 27) consisted of two magnets with the superconducting M1 situated 2.7 m downstream of LEBC providing 1.1 T in a horizontal aperture of 0.8 m. M2, situated 20 m downstream of LEBC was a conventional U-magnet of 1.3 T. The Proportional Inclined Chamber PIC was positioned at the centre of M1, inclined by 35° to the vertical. The LEBC tracks were matched to PIC via two small drift chambers located immediately behind

Figure 28. A neutral $D^0/\bar{D}^0$ charm pair.

Figure 29. The print-out of the same charm pair (Fig. 28) from the Strasbourg HPD.

the bubble chamber and by two multiwire proportional chambers W0 and W1 at 0.37 m and 0.87 m downstream, respectively. The magnetic track bends were determined with the large drift chambers D₁ to D₆. Particles were identified with the Silica Aerogel

Cherenkov Detector (SAD), the large pictorial drift chamber ISIS, the 12 m long Forward Cherenkov (FC) with helium as radiator and with the Transition Radiation Detector (TRD) for electron identification.

During the NA 27 runs, LEBC was operated

Figure 30. A charged C5 charm decay together with a neutral V2.

Figure 31. Distribution of impact parameters as measured by the Strasbourg HPD demonstrating the high two track resolution with LEBC-optics.

at 30 Hz cycling rate, 29.1 K temperature in the visible region, 8 mm^{-1} to 10 mm^{-1} bubble density and $15 \mu\text{m}$ bubble diameter. To achieve the high speed film transport required for the 15 Hz camera rate, a new drive mechanism was developed [40], which moved the frames by rotating a capstan stepwise through 60° , to bring the next face into position for photography. Figs 28 through 30 show some charm decays photographed in this way. The distribution of impact parameters as measured by the Strasbourg HPD shown in fig. 31 demonstrates the high optics resolution achieved with LEBC.

Between autumn 1984 and spring 1985 LEBC was transferred with its whole equipment to Fermilab in order to perform experiment E743 in a 800 GeV/c proton beam from the Tevatron. There it was again mounted as a track sensitive vertex detector in front of the Multi Particle Spectrometer (MPS), which was not as sophisticated and powerful as EHS. It contained one superconducting magnet giving 0.7 GeV/c transverse momentum, ten tracking

Figure 32. A neutral V4 charm decay photographed in the 800 GeV/c-proton beam at Fermilab.

stations, two Cherenkov counters and one TRD. The momentum resolution was 1.5% and the momentum thresholds for π , K, p were 5, 25, and 38 GeV/c for the first and 17, 59, 112 GeV/c for the second Cherenkov counter. After a 11 month transfer time from CERN to Fermilab, LEBC achieved the same picture quality as before (fig. 32).

An interesting continuation of LEBC has been pursued at Protvino, Russia [41]. A Lexan chamber body was designed (fig. 33), where the expansion forces have been compensated by two pistons acting in opposite directions. First beam tracks were photographed in December 1988 and in April 1992 a 70 GeV/c-proton exposure with this chamber as a vertex

detector of a spectrometer took place. 180 K-pictures were taken with conventional optics 15 mm^{-1} bubble density and $25 \mu\text{m}$ bubble diameter. Until now, this chamber has been cycled more than 6 million times with about 300 K-photographs taken at tests and production runs together.

4. OUTLOOK ON THE FUTURE OF PARTICLE TRACKING

The era of bubble chambers was coming to an end in the late eighties with the request to detect rare particles with cross-sections in the nano-barn range, in particular those containing

Figure 33. Cross-section of the Precision Bubble Chamber (PBC) Lexan body at Protvino.

1 - Lexan chamber body; 2 - internal heat exchanger; 3 - Lexan membrane; 4 - piston; 5 - vapour pressure bulb; 6 - heat exchanger of the capillary; 7 - filter; 8, 12 - inlets of the pressure and temperature gauges; 9, 11 - inlets of the internal heat exchanger; 10 - cold filling valve.

Figure 34. Square fibre bundle with 2.5 mm edge length containing about 1600 individual fibres of 60 μm diameter. The photograph is taken through 2 m bundle length. The arrow indicates the bundle orientation normal to the beam axis and the angle ω .

beauty quarks. Also, the increasing application of colliding beam accelerators prevents their use as detectors at the relevant beam crossing points. Therefore, they are now replaced by electronic detectors, which are able to follow much better the high production

rate induced by the bunch frequencies of the colliders. There exist now mainly three media to replace bubble chambers for particle tracking: gas chambers, semi-conductors and scintillating fibres.

The particularly interesting microstrip gas chambers consists of 5 to 10 μm wide anode and some 50 μm wide parallel field strips, deposited via lithography or plasma etching on an isolating substrate. In this way, cells of about 200 μm pitch and 2 to 3 mm gas depth (cathode distance) are formed. Drawbacks are their sensitivity to magnetic fields (Lorentz angle) and electron drift times of about 50 ns.

Detectors based on semi-conductors are operated as diodes with reverse bias voltage. Electrons and holes induced by the passage of ionizing particles, drift in silicon within a bias field of 300 V mm^{-1} across the 300 μm thick depletion layer. The tracking elements are geometrically arranged as single or double-sided strips of 25 μm to 100 μm pitch and are several centimeters long. All elements are bonded or even monolithically integrated to their relevant front-end electronics. These numerous electronic channels produce heat, which must be removed by cooling loops, to prevent unwanted temperature rise of the silicon elements leading to increasing leakage currents.

Figure 35. r - z plane. The tracker covers up to 1.75 rapidity. Readout with electromagnetically focused delay tube is at $z=0$ of each shell. ϑ means the polar angle.

Particle detection with scintillating material has been refined during the last years by the fibre technique, where transparent scintillating cylindrical cores with diameters between several micrometres and a few millimetres are surrounded by a cladding layer of lower refractive index. Therefore, such a fibre traps by total reflections on its core-cladding interface a small fraction of the scintillating light, again induced by ionization losses, and guides it via many subsequent total reflections to the fibre end. There, it is in most cases detected by the photocathode of a multiplier or an image intensifier. Fibre cores for particle tracking are produced from plastic polymers, e.g. polystyrene (PS) and are cladded with polymethyl methacrylate (PMMA).

The cell elements of a fibre tracker are defined by the lengths and diameters of its individual fibres. Since the diameters reflect on the trackers occupancy, its spatial- and two track resolution, we want to keep them small. The lower diameter limit is dictated by reflection losses due to imperfections at the core-cladding interfaces. Since the number of light reflections is inversely proportional to the fibre diameter a value of $40\text{ }\mu\text{m}$ to $80\text{ }\mu\text{m}$ represents a good balance between reflection- and absorption losses in the core. Such thin fibres must be produced as fused coherent bundles (fig. 34) of rectangular cross-sections

Figure 36. Arrangement of scintillating fibre shells for tracking within the free barrel region of the calorimeter. r - ϕ plane seen at $z=0$. the magnified parts show the subdivision into the straight ϕ and the oblique u and v layers. The symmetric angles β indicate the z coordinate via the indicated relation.

Figure 37. Track segment read out from a fused fibre bundle with 2.5 mm edges. A $5\text{ GeV}/c\text{ }\pi$ beam traversed the bundle like an ionizing particle the layer of the tracker arrangement in fig. 36.

with edge dimensions between 1 mm and 3 mm [42].

A fibre tracker which covers the central barrel region of a particle detector around the beam crossing point [43], consists of cylindrical shells (fig. 35 and 36) with different diameters. Each of them is composed of layers with different fibre orientations (fig. 36). Fibres stretched parallel to the collider axis measure the (ϕ, r) -coordinates. The two other layers with oblique orientation, running at angles of a few degrees with respect to the parallel ones, provide via their corresponding stereo view the z-coordinate of a particle track. This arrangement results in a tremendous reduction of readout channels as compared to silicon detectors.

Finally, figure 37 shows the 5 GeV/c π -track segment of a fused fibre bundle with 2.5 mm edges. As compared to fig. 24 it shows a ten times larger track corridor. But with 2.5 ns decay time of the scintillating light, data acquisition is one million times faster as with bubble chambers.

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