SIMULTANEOUS OPERATION OF A LIQUID ARGON DETECTOR AS BUBBLE CHAMBER AND CALORIMETER

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The first successful operation of a new detector, filled with liquid argon is described. It can be used simultaneously as bubble chamber and calorimeter, and may find interesting applications at high-energy accelerators.

1. Introduction

The new generation of fixed-target accelerators in the TeV energy range requires multiton detectors, which give specific information on the topology of events, allow particle identification, momentum determination and provide timing information. This is of special interest for neutrino interactions, containing strange particles and multileptons, where one or more of the leptons are electrons [1]. For financial, technical and safety reasons cryogenic bubble chambers filled with hydrogen, deuterium or neon-hydrogen mixtures can probably not be built with much larger volumes than some 35 m³ (Big European Bubble Chamber at CERN, 15-foot Bubble Chamber at Fermilab). Another difficulty lies in their limited precision in measuring the momentum of a very energetic electron [2] (fig. 1) or of a hadronic shower. An attractive way out of these problems could be the use of liquid argon in a new type of detector, which can be operated simultaneously in the bubble chamber and calorimeter modes. The relatively high specific density and short interaction length of argon makes muon identification inside large volumes fairly easy. Furthermore, timing information on (rare) interactions can be reliably and rapidly obtained from the scintillation pulse produced during the passage of particles [3]. This signal can be used to trigger the flash of the bubble chamber, provide a gate for the charge collection, and give even crude results on energy contained in heavy showers and thus complement calorimetry from the charge sensitive amplifier.

Such a detector may also find application at colliding beam machines, e.g. at the SLAC linear collider, where it could be built around the vacuum tube of the interaction region, or it could be used even in proton decay experiments, provided that its volume can be made large enough.

The feasibility of producing good particle tracks in a

Fig. 1. Monte Carlo simulated electron shower (primary energy 50 GeV) in a heavy neon/hydrogen mixture ($X_0=40$ cm), magnetic field 30 kG [2].

2.7 t argon test chamber was demonstrated recently [4]. In the present paper we show that charge collection with reasonable accuracy is possible during bubble chamber expansions. The experimental set-up is described, results of measurements in a 200 MeV/c pion test beam are given, and future improvements in charge collection, mainly by employing the scintillation pulse as a trigger, are discussed.

Fig. 2. Photos of 200 MeV/c pions in liquid argon at 135 K. Bubble density (18 ± 2) bubbles/cm. bubble size $\phi \approx 0.3$ mm. Charge collection wire with $\phi < 1$ mm in the centre of the bubble chamber: (a) low beam intensity (~ 20 tracks), (b) medium beam intensity (~ 60 tracks), (c) high beam intensity (~ 150 tracks).

2. The experimental arrangement

2.1. The beam

At present our detector is installed at the 600 MeV synchrocyclotron at CERN in a 200 MeV/c pion beam. The repetition rate of the accelerator is 183/s, i.e. the

time interval between successive pulses is ~ 5 ms, well matched to the sensitive time of approximately 4 ms during a 15 ms expansion-recompression cycle of the bubble chamber: only one particle burst can produce tracks during such a cycle. During short running periods the accelerator was operated with only one particle burst every 2 s, which is the present repetition rate of our bubble chamber. The duration of the particle burst is ~ 40 μ s fwhm, having a Gaussian-like intensity distribution, a microstructure of 60 ns, and a jitter of 60 ns.

The beam intensity is monitored by coincidence counters in front of the vacuum tank of the detector. The diameter of the beam is chosen to be ≤ 8 cm, so that the particles fill homogeneously the visible volume of the chamber. Those particles, going through the centre of the cylindrical chamber (axis perpendicular to the beam) have to penetrate a 2 mm aluminium vacuum tank window and 11 mm of stainless steel of the chamber vessel. This causes a momentum loss of $\sim 10\%$ and a mean scattering angle of $\sim 0.5^\circ$ prior to the entrance into the liquid. These values are larger by a factor of up to 1.5 in the border region of the visible volume. The occasional use of collimators allowed a reduction of the beam profile to 2 cm and an adjustment of the beam position relative to the charge collection wire.

Fig. 3. Piston stroke (0.5 mm/division) and dynamic pressure (~ 4 bar/division); time scale: 2 ms/division.

2.2. The detector

2.2.1. The bubble chamber

The bubble chamber is described in detail in ref. 4. It was operated with argon at a liquid temperature $T \approx 135$ K (vapour pressure $P_v = 25.6$ bar) and static pressure $P_s = 26.5$ bar. With a volume change of $\Delta V/V \leq 1\%$ (2 mm piston stroke) we obtained an expanded pressure $P_e \approx 10$ bar (the piezoelectric pressure transducer had not yet been precisely calibrated). The duration of the expansion-recompression cycle was $t_e \approx 15$ ms unless otherwise stated. The beam was injected at the pressure minimum and the flash delay was $\Delta t_f = 1.5$ ms. Tracks were photographed with a single camera. The above conditions result in tracks with bubble sizes of ≈ 0.3 mm and a bubble density of (18 ± 2) bubbles/cm, the latter not being corrected for the unknown dip angles. The picture quality allowed a fairly reliable count of the number of particles going through the chamber up to ~ 100 tracks per photo. Typical photos are shown in figs. 2, the piston stroke and the dynamic pressure vs. time in fig. 3.

Argon with a purity of $> 99.9999\%$, as guaranteed by the manufacturer (contamination with $O_2 < 0.1$, $N_2 < 0.3$, $H_2 < 0.001$, $CH_4 < 0.005$, $H_2O < 1$ ppm), was used; no additional analysis of the gas was carried out.

2.2.2. The charge collection device inside the bubble chamber

Most of the physics aspects of liquid ionization detectors are described in great detail in the literature (e.g. refs. 5, 6, where extensive bibliographies are given).

and recent results on drifting of electrons over large distances are reported (e.g. refs. 7, 8). Therefore we describe here only our technical layout.

Fig. 4. Vertical cross section of the bubble chamber with charge collection wire: 1: chamber body, 2: expansion piston, 3: scotchlite, 4: $\phi = 1$ mm charge collection wire, 5: support studs for wire, 6: flexible cable to HV power supply and charge sensitive preamplifier, 7: chamber window, 8: heat exchanger.

Fig. 6. Electronic configuration for charge collection, including interface to computer.

distribution, there is a charge build-up in the charge sensitive preamplifier because of its long time constant ($\sim 50 \mu\text{s}$). Fig. 6 shows an idealized wave form pattern. At the end of the scaler gate the preamplifier output voltage was sampled by a charge-sensitive ADC. Scaler and ADC values were read out via CAMAC to a Hewlett-Packard computer.

A second set-up did not require the accelerator beam and was used to show that the signal due to the variation of the chamber capacitance during an expansion cycle could be filtered out so that it did not contribute to the charge created by beam particles. A precision pulse generator was used to inject the charge into the preamplifier via the calibration input. The output signal

was shaped by a double differentiating amplifier with a 600 ns shaping time constant. This shaping amplifier is a bipolar RC clipped circuit, which had been previously used with a liquid argon calorimeter [10]. The height of this signal was measured by an ADC and read out via CAMAC.

3. Experimental results

3.1. Noise sources

The primary aim of our tests was to show that the mechanical expansion of the bubble chamber is compatible with the collection of free charges produced during

Fig. 7. Signal from charge sensitive preamplifier (1 V/division), 10 kV on wire, produced by change of capacitance during bubble chamber expansion, cycle duration 15 ms, together with piston displacement (0.5 mm/division), and dynamic pressure (~ 4 bar/division). Time scale: 2 ms/division, ΔC is the maximal amplitude of the unwanted signal prior to particle injection.

the passage of high energy particles. The main concern had to be, therefore, to identify unwanted electric, electronic and microphonic noise sources, which could couple to the charge sensitive amplifier. Such disturbances, coming from the electric part of the hydraulic expansion system and from various power supplies were found and eliminated. The box, containing the charge amplifier and capacitors, is mechanically attached to the vacuum tank and screened against high-frequency noise. The vibration of the box, which is very small during the expansion of the chamber, does not affect the charge measurement. The movement of the charge collection wire relative to the chamber vessel during the expansion is not known but, considering its rigid support structure, should be very small. When all electric and electronic equipment and the detector was running, with 10 kV on the charge collection wire, but without the mechanical expansion of the chamber, the remaining noise with a main frequency of ~ 250 Hz, was 15 mV_{rms}, i.e. less than 0.5% of the total range of the preamplifier.

To produce good bubble tracks in our chamber the piston must be rapidly moved by ~ 2 mm. Considering the chamber height of 100 mm, this displacement corresponds to a capacitance change of less than 2%. The resulting unwanted signal on the charge sensitive amplifier is shown in fig. 7 for a 15 ms expansion-compression cycle and a high voltage of 10 kV. This signal looks essentially like a derivative of the displacement curve. The amplitudes of the parasitic signal increase linearly with the applied HV, and their dependence upon the cycle duration is shown in fig. 8. The

quite significant drop of this disturbance with increasing cycle duration favours the prospects for very large bubble chambers. There, longer duration of the cycle is required for various reasons, in particular for growing bubbles to the necessary larger sizes compared with those in our small test device, and because of pressure

Fig. 8. ΔC (compare fig. 7) as function of the duration of the expansion cycle.

homogeneity (sound velocity). At constant volume change, but increasing cycle duration, there is a decrease of the pressure drop due to the increased influence of parasitic boiling. In our chamber, this amounts to a 15% less when the cycle length changes from 15 to 100 ms. In spite of this fact, we still obtained sensitivity at 300 ms cycle duration. In much bigger chambers this drop should be far less pronounced because of the more favourable volume/surface ratio.

The influence of the change in capacitance appears to be less dramatic when we consider the following facts: (a) the piston is almost at rest when the pressure minimum is reached, (b) the disturbing signal is very reproducible for constant chamber conditions and (c) has its smallest amplitude during the time of particle injection, and (d) the time interval between particle burst and collector of all charges is relatively small and so is the change in the disturbing signal. However, to trigger a gate between the charge amplifier and a double differentiating amplifier of suitable shaping time to collect all charges remains necessary for any precision measurement.

The unwanted signal from the change of capacitance between expansion bellows and wire, particularly in our test set-up, can be largely suppressed in any future big chamber either by a non-conductive piston structure or/and by a screening grid between the moving part and the charge collector.

Another disturbance arises from the trigger pulse for the bubble chamber flash. This pulse is difficult to screen and it saturates the charge amplifier (~ 7 V); the signal decays within 0.5 ms. However, this disturbance comes a long time (some milliseconds) after the gate for charge collection, and therefore cannot anymore influence the charge measurements.

3.2. Performance of the amplifier during calibration pulse

A precision pulse generator was used to inject charges into the preamplifier via the calibration input. The preamplifier signal was shaped by a double differentiating amplifier, which happened to have a 600 ns shaping time constant. This time is well adapted for electron drift distances in the millimetre range, but has to be increased for physics experiments, when drift distances over centimetres or even a metre are envisaged. Here, our purpose is only to demonstrate that the signal due to the variation of chamber capacitance during an expansion cycle could be filtered out so that it did not contribute to the charge created by particles.

The maximum pulse height of the injected signal was 6.3 mV at 2 pF, which corresponds to 0.0125 pC. A similar charge would be produced by a minimum ionizing particle with ~ 2 cm track length, if we use as mean energy loss by ionization $\Delta E = 2$ MeV/g cm^{-2} , an argon density $\rho = 1.0$ g/cm³ at 135 K, and an average

energy for forming an ion pair $\bar{E} = 25$ eV, resulting in 4×10^6 electrons/cm.

The height of the output signal was measured by an ADC and read out via CAMAC. A series of 50 measurements were made per point. Each series was treated to give the mean deviation from the average value. Measurements were made as follows (all numerical values in ADC units):

- (a) Only the amplifier in circuit, i.e. no connection to the liquid argon chamber, with expansions, cycle duration 15 ms, no high voltage on wire:
 - (i) charge injection at $P_{\min}$ 612 ± 4 ;
 - (ii) charge injection at half ΔP after $P_{\min}$ 700 ± 4 .
- (b) Liquid argon chamber connected to amplifier circuit, no expansions, 10 kV on wire:
 - (i) motor of the hydraulic pump off 317 ± 10 ;
 - (ii) motor of the hydraulic pump on 316 ± 14 .
- (c) Liquid argon chamber connected to amplifier circuit, with expansions, cycle duration 15 ms, 10 kV on wire:
 - (i) charge injection at maximum piston stroke 323 ± 13 ;
 - (ii) charge injection at $P_{\min}$ 322 ± 15 ;
 - (iii) charge injection at half stroke before $P_{\min}$ 312 ± 14 ;
 - (iv) charge injection at half stroke after $P_{\min}$ 301 ± 15 .

Fig. 9. Performance of the charge sensitive preamplifier during injection of calibrated signals of various amplitudes, chamber disconnected: (a) injection of test pulse at pressure minimum, (b) injection of test pulse at half piston stroke after pressure minimum; and chamber connected: (c) injection of test pulse at pressure minimum.

- (d) Liquid argon chamber connected to amplifier circuit, with expansions, cycle duration 80 ms, 10 kV on wire;
 (i) charge injection at maximum piston stroke 311 ± 17 .

The main features of this tests are: there is a linear relationship between injected and measured charges for conditions a(i) and a(ii) (see also fig.9). When the charge collection wire is electrically connected, its capacitance (22 pF measured with liquid) reduces the output signal of the preamplifier as expected. The chamber cannot be considered to be a good Faraday cage, since the relative rms noise level increases from $\pm 0.7\%$ to about $\pm 5\%$ after it is connected with the charge sampling electronics. High frequency noise may enter the liquid via the chamber window, cables for the pressure transducer, or via the high-tension wire. With expansions, the amplitude of the signal is highest near the pressure minimum, and lower at half of the piston stroke on both sides of the minimum. This result may be explained by the then more prominent change of capacitance produced by the piston movement (compare fig.7). There was no significant change of the signal with different duration of the expansion cycle, probably because of the short shaping time constant.

Two preamplifiers were tried which had gains differing by a factor of 2.5; they both showed similar features. The pedestal was ~ 20 ADC units.

3.3. Charge collection from particles with a non-expanded chamber

An approximate 3:1 relation was established at low beam intensities between the coincidence counters in front of the detector and the number of particle tracks photographed with the bubble chamber camera. The highest number of tracks which could be reliably counted on film is ~ 100 . However, the above relation is assumed to hold for much higher numbers.

The beam intensity is monitored by the coincidence counters and was always stable over long time intervals within $\pm 0.5\%$ and $\pm 3\%$ for high and low intensities, respectively; however, variations from pulse to pulse could attain some $\pm 30\%$. A plot of the coincidence counts against the scaler readings shows linear behaviour.

The tracks fill the visible volume of the bubble chamber almost homogeneously, as deduced from the photos (compare figs. 2). The tracks are essentially parallel to the charge collection wire.

Measurements of the collected charges were made without expansion for four different beam intensities, during which the voltage was increased from 0 to +10 kV in steps of 1 kV. For the lower intensities 50 beam pulses were accumulated and registered with the computer, at the highest beam intensity only ten pulses. The

Fig. 10. ADC readings vs. high voltage, beam intensity as parameter, without expansion.

Fig. 11. Typical signal from the charge sensitive preamplifier, ~ 100 tracks, without expansion: (a) 1 beam spill only (b) 10 beam spills superimposed; scales: 50 μ s/division, 50 mV/division.

results are depicted in fig. 10; amplitudes of the collected charges are given in ADC units with statistical errors only. The variations at each measured point are essentially due to the fluctuations in the beam intensity from pulse to pulse, and to variations of the maximum of the build-up charge in the amplifier relative to the fixed position of the 100 ns gate to the charge sensitive ADC. Fig. 11(a) shows the charge build-up during one accelerator spill; fig. 11(b) when ten spills are superimposed on the oscilloscope. The relative uncertainties of ADC readings increase from 8% at high beam intensities to 14% at low intensities. A linear fit is made through the measurements at each of the four beam intensities. The noise level corresponds to ~ 50 ADC units.

For different beam intensities the ratio of the spaces of collected charge is in good agreement with the corresponding ratio of the coincidence counts, i.e. we measure real charges from beam particles. There seems to be a linear dependency of collected charges upon the applied voltage up to 10 kV. At very high fields we would expect a deviation from this linearity and an asymptotic behaviour.

At present our results can be explained only qualitatively because charge collection depends in a complex manner upon various parameters: (a) the electric field distribution, (b) the distance of particles from the collection electrode, and (c) the purity of the liquid.

In a crude approximation our detector has a cylindrical field distribution, where we may define a bubble chamber "radius" with $R = 5$ cm, having in its centre a wire with $r = 0.05$ cm. When we apply a voltage of 10 kV, then the radial field would be $E(x) = 2.2 \text{ kV/x}$, where x is the distance from the wire in cm.

The drift velocity of electrons in liquid argon may be described in good approximation for field strengths between 0.3 and 30 kV/cm by [11,12]

$$v_d[\text{cm/s}] \approx 2.1 \times 10^5 E^{1/2},$$

An increase of the applied voltage causes a decrease of both the drift time and electron attachment on electronegative impurities. The attenuation of collected electrons can be expressed by [13]

$$q(x) = q(0) e^{-x/L},$$

$$\text{where } L(\text{cm}) = 0.15 \frac{E(\text{kV/cm})}{p(\text{ppm O}_2)}$$

and p = electronegative impurities concentration (mainly oxygen).

Oxygen impurities in our chamber filling should not exceed 0.1 ppm, since this was guaranteed by the manufacturer, and proper care was taken during the purging of the chamber to avoid any additional contamination. Then, with 10 kV on the wire, electrons created 1 cm away from it have a mean free path of

$L = 3$ cm, i.e. at least 70% of these electrons will be detected.

Drifting electrons induce an image current on the collection wire, depending at which distance they are created, given by

$$I(x) \approx q \frac{v_d(x)}{x \ln(R/r)}.$$

Taking into account a particle flux homogeneously distributed in a plane perpendicular to the wire, and the above three relations, one may expect a linear increase of the number of collected electrons upon increasing voltage to ~ 10 kV. However, the position of the maximum amplitude of the signal may shift somewhat in time. Any more quantitative statements require tests with a "pencil" beam of very short spill duration, which can be injected into the chamber at various distances from the wire. Furthermore, an electrode arrangement giving a well-defined field distribution would be advantageous.

3.4. Charge collection from particles during bubble chamber expansions

Measurements of charge collection at the presently highest possible voltage on the wire (10 kV) with full expansion of the chamber were made. At some beam intensities several hundred photos were taken consecutively.

Most of the measurements were made at low and moderate beam intensities, mainly to study the sensitivity of our device and its signal-to-noise ratio. The results are plotted in ADC units versus beam intensity (fig. 12). For comparison we show also the linear dependence of ADC counts on intensity obtained without expansions, as extracted from fig. 10. Fig. 12 demonstrates that

Fig. 12. ADC readings for various beam intensities during bubble chamber expansions, 18 ms cycle duration, 10 kV on wire. Solid line: results without expansion, taken from fig. 10.

charge collection during expansion is possible, and compared to a quiet chamber, practically all ADC readings during expansion are higher, and their rms fluctuations are larger by a factor of two. The beam intensities at which photos 2(a-c) were taken are indicated.

No attempt is made at present to calibrate our measurements absolutely, mainly because of the long beam spill and of variations in beam intensity from spill to spill.

In any future large chamber the time spread in the arrival of free electrons from a real event is expected to be smaller than our present beam spill; however, its value depends on the electrode spacing. The timing information from an event derived from its scintillation signal should be used to initiate a gate between the charge sensitive preamplifier and a double differentiating amplifier with suitable shaping time, adjusted to collect all free electrons from such an event. The adverse influence of the change of capacitance during expansion can probably be considerably reduced also by a properly adapted cage, to be kept at ground potential, thus screening the piston movement; or by a piston made of non-conductive material. With these possible improvements in mind, we believe that the present disturbances can be substantially reduced.

3.5. Electron drift and bubble formation process

The presence of a high electric field (+10 kV on the wire and support stems, distance to the chamber body 5 and 1.5 cm, respectively) appears to cause neither a noticeable reduction nor an increase of bubble densities along the particle track as compared to no-field conditions. However, with our single view optic, it is neither possible to determine the distance of tracks from the charge collection wire in the central part of the chamber, nor to see tracks between the support stems of the wire and the adjacent chamber wall, where the electric field is highest. As was pointed out by Hofmann and Hugentobler [14], it is not yet shown experimentally in a conclusive manner, whether the bubble formation by δ -electrons is due to an accumulation of ions of the same charge and their repulsive forces, or due to local heat concentration produced by ion recombination. As suggested to us by Doke [15], this question might be clarified during a repetition of our experiment, to be done at fields higher than about 3 kV/cm, where ion pairs can be separated, and by using at the same time a better defined field geometry. At present we can try only to explain the absence of obvious variations in bubble densities by discussing two possible effects of electric fields upon the bubble formation: (a) change of the direction and speed of δ -electrons and (b) escape of electrons and holes from recombination.

(a) In order to grow bubbles along a particle track to visible size, the necessary condition is, that the initial

bubble formed by δ -electrons has to attain at least the critical size. The critical radius r_c is shown by thermodynamical considerations to be

$$r_c = \frac{2\sigma}{p_v - p_e},$$

where σ is the surface tension, and p_v and p_e the equilibrium vapour pressure and the expanded pressure, respectively. We estimate the critical radius at our operating conditions to be ≈ 30 Å. We have to investigate whether a unidirectional movement of the δ -electrons due to the electric field alters the conditions for the dissipation of heat in a sphere of this size. The relaxation time for the dissipation of heat contained in such a prenucleation volume is $\tau = r_c^2/D$, where D is the diffusion coefficient of heat. The latter is related to the thermal conductivity λ by the equation $D = \lambda/\rho c_p$, where ρ is the density of the liquid and c_p the specific heat at constant pressure. For our operating temperature we use $\lambda = 65 \times 10^{-3}$ W/m·K, $c_p = 1.72$ J/g·K [16] and find $\tau = 2.4 \times 10^{-10}$ s.

The drift distance of δ -electrons within this relaxation time can be estimated, assuming in our case an electric field of 2 kV/cm and a drift velocity of $v_d \approx 2 \times 10^5$ cm/s, as measured at the normal boiling point and neglecting its temperature dependency [12]. We obtain $s = v_d \cdot \tau \approx 5 \times 10^{-5}$ cm, a displacement which is considerably larger than the critical bubble diameter of $\varnothing \approx 6 \times 10^{-7}$ cm. The δ -electron would leave the prenucleation volume if it had its centre at the origin of ionization. However, as shown by Monte Carlo calculations for hydrogen and deuterium [17], the size of the excitation/ionization cascade during the slow-down of δ -electrons exceeds anyway such a volume, and only at its end, when the electrons have travelled a distance of $s \approx 3 \times 10^{-6}$ cm, does the densest area of excitation remain inside a prenucleation volume. Similar behaviour may be expected for liquid argon, the difference as compared with the lighter cryogenic liquids being its higher density, its smaller critical bubble radius, and that during calculations the Auger effect should be considered in addition to excitation and ionization. Since we do not see any decrease of the bubble density in the presence of the electric field, we conclude that the unidirectional component of the electron's movement, caused by the electric field, only displaces the position of the prenucleation volume in space. This displacement along the electric field lines can be neglected during the reconstruction of particle tracks since it is by orders of magnitude smaller than any displacement of macroscopic bubbles due to buoyancy forces, liquid movement and turbulences.

(b) There could also be an increase of bubble density with electric field, because the amount of energy going into scintillation decreases with field strength [18] due to the escape of electrons and holes from recombination.

tion. More energy could be available for ionization and, hence, for bubble formation. Scintillation light produced by 200 MeV/c pions has been measured in our detector [3], however, until now without electric field. Tests are being prepared to operate the charge collection device and light detection simultaneously, and to measure the field dependency of the scintillation signal.

At present we also cannot rule out the possibility that both effects may be actually there, but that they cancel each other.

4. Conclusions

It is shown that charge collection during bubble chamber operation of a liquid argon detector is possible, but that noise still affects adversely the measurements, particularly during long beam spills. The disturbance comes mainly from the change of capacitance during the expansion, whereas most of the other sources were virtually eliminated during our tests. It is demonstrated that noise becomes smaller with longer expansion-recompression cycles, favouring the prospects for very large chambers of this type. Further improvements will be obtained using the scintillation signal as trigger of a gate for the charge collection electronics, and by a modification of the layout of the electrodes. The presence of the high electric field (10 kV on the wire) does probably not alter bubble densities along particle tracks.

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