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INVESTIGATION OF VERY LONG JET CHAMBERS

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ABSTRACT

The electrostatic properties and the performances of very long Jet Chambers have been investigated. Using 100 MHz FADC waveform digitisers, the tracking accuracy, the charge division and the dE/dx performance of two chambers, one with 4.5 m long tungsten wires and one with 4 m long high resistive "NiCoTi" wires have been studied. The geometry of the chambers was chosen to define some of the design parameters of the Jet Chamber for the OPAL detector for LEP.

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1. INTRODUCTION

The Jet Chamber concept, which has been adopted for the OPAL detector [1], was pioneered by the JADE experiment [2] and is well understood for wire lengths of about 2 - 3 m and a sense-to -potential wire spacing of 5 mm. However increasing the chamber length to 4 m or more, as foreseen for the Central Detector of OPAL at LEP, is not a trivial extrapolation. The electrostatic deflection and the gravitational sag of the wires become important and the mechanical tension applied to the wires has a natural limit as one approaches the breaking point.

In view of these difficulties it was crucial to investigate the behaviour of such a long chamber on a prototype with a small number of wires before starting to build the OPAL Jet Chamber. Two chambers with 8 sense wires each have been built : one, 4.5 m long, with tungsten sense wires and one, 4 m long, with nickel-alloy (NiCoTi) sense wires. The higher electric resistivity of the NiCoTi wires is advantageous for charge division - the method to be used in the OPAL Jet Chamber to determine the coordinate along the wire - but the lower mechanical strength pointed towards possible electrostatic problems which had to be investigated.

This paper describes the experience gained during the construction and the running of these chambers. In the choice of the operating conditions one had to keep in mind all requirements imposed on the future OPAL Jet Chamber, namely good tracking resolution and good ionisation measurement for particle identification. It should be pointed out that the emphasis of this study was not to obtain fine-tuned operating conditions but rather to assess the feasibility of a 4 m long Jet Chamber which would satisfy the above requirements.

In the next section the design considerations will be discussed. The actual construction and the operation of the chambers will be described in section 3 and 4. Finally the data analysis will be presented in section 5 and the results obtained for different operating conditions will be summarized in section 6.

2. DESIGN OF THE CHAMBER

2.1 Chamber Geometry

The layout of the chambers, which both had the same wire configuration with a drift gap of 33 mm, is shown in Fig. 1. Table 1 summarises their basic mechanical parameters. The chamber geometry was chosen to simulate the OPAL Jet Chamber at the inner radius, where the mechanical tolerances are the most critical.

The open cell geometry simplifies the optical survey of the wire position and allows easy access with a laser beam. The electrostatic questions of closing the Jet cell of the final OPAL detector at the inner radius were studied separately and will be discussed in the next section. In order to minimize field distortions and electrostatic deflections six wires of appropriate thicknesses and potential settings, terminated the anode- potential-wire plane. For the same reasons a mirror plane was added at each side of the cell.

Since the Jet Chamber has to measure simultaneously drift time, charge division and energy loss, the design specification required a careful optimization of many parameters :

- a) The gravitational sag should be equal for sense and potential wires. Small systematic differences of the order of 50 μm can however be tolerated between the anode and the cathode planes.
- b) The mechanical tension of the wires should be high enough to keep the electrostatic deflection and the gravitational sag small but should stay at least 30% below the breaking point.
- c) The sense wires should have high electric resistivity to allow for good charge division.
- d) The value of the electric field on the surface of the potential and cathode wires has to be below the threshold for field emission of about 20 kV/cm.

- e) The chamber should be operated at the plateau of the drift velocity curve.
- f) Because of the energy loss measurement a good charge collection optics has to be reached.
- g) The gas gain has to be a compromise between a good charge division resolution, which needs a high gain and the dE/dx measurement which prefers a lower gain because of saturation.

In order to meet all these design criteria the electrostatic properties of the cell were simulated using a computer program which will be described in the next section. The mechanical properties of the wires have also been studied. As an example Fig. 2 shows the elasticity behaviour of a Cu-Be wire and of a NiCoTi wire. As a result of these studies two chambers have been built : "chamber I" with W(Re) sense wires^{*)} and Cu-Be potential and cathode wires and "chamber II" with NiCoTi sense^{**)} and potential wires and Cu-Be cathode wires. The latter combination has been chosen in view of the very large number of cathode wires (~ 12000) in the OPAL detector, because NiCoTi wires are difficult to solder. As the Cu-Be wires can not be loaded to the same tension as the NiCoTi wires, the second prototype is gravitationally not balanced, although the systematic discrepancy of the gravitational sag of about 30 μm between the anode and the cathode planes is considered to be tolerable.

2.2 Calculations of Electrostatic Deflections

The electrostatic deflection of the wires are mainly caused by the staggered position of the sense wires and by the boundaries of the chamber. The effect increases quadratically with the length of the wires and sets a practical limit to the length of chambers. The length of the OPAL Jet Chamber will come close to this limit and this motivated a careful simulation of the electrostatic deflection.

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A first order approximation, for which deflections are calculated from the charges situated at the undeflected wire positions did not yield the observed displacements of the wires. Hence an iterative process was introduced in which, for each step, the charge distribution was recalculated for the wires in their new positions. The results of such a study for 4 different chamber configurations are summarized in Fig. 3, which shows the additional transverse deflection of a sense wire with respect to the anode plane after each iteration step. For example the calculations predicted progressively increasing deflections for chamber configuration A) of Fig. 3. Indeed for this configuration sparking between the wires was observed, well below reaching the operating voltages. It can also be seen that the NiCoTi solutions, even though they are only 4 m long, need many more iterations than the 4.5 m long W(Re) solution, because higher tensions can be put on the W(Re) wires. Fig. 4 shows the excellent agreement between the measured and the calculated deflections for the wire configuration D), which corresponds to the chamber I with the operating point 1 of table 3. This example shows the predictive power of the iterative method. Without iteration the calculation would yield a discrepancy of a factor of 2 between the measured and the calculated deflection.

The electrostatic program was also used to study the termination of the Jet cell using guard wires, as shown in the insert of Fig. 5. Their potentials should be chosen so, that the nominal drift field be preserved in this guard wire plane. However, even small variations of the terminating electrostatic field cause large deflections. This is demonstrated in Fig. 5, where the calculated deflections in the anode plane of the 3 outermost sense wires are plotted for some values of the field in the guard wire plane. It is seen, that the deflections of the sense wires decrease with increasing distance from the guard wire plane. The slight horizontal shifts are due to the asymmetrie introduced by the staggering of the wires. A field variation of only 5% generates a deflection of 280 μm for the outermost sense wire of chamber I and 310 μm for chamber II. As chamber I is 50 cm longer than chamber II this is a further argument in favour of the tungsten solution.

It is worthwhile to point out that the iterative calculation of the electrostatic deflections is not a special requirement only for very long chambers. A very similar situation occurs, for example, for small vertex chambers, where the resolution and the multiple hit capability is improved by reducing the wire spacing but increasing the gas pressure, thus requiring higher voltages. However for conventional chambers of about 2 - 3 m length, iterative calculations are usually not needed to explain the observed electrostatic deflections.

3. DESCRIPTION OF THE CHAMBERS

Fig. 6 shows two photographic views of the chamber. A massive aluminium beam supports two 30 mm thick aluminium flanges to which the wire suspension system was attached. In view of the large number of wires in the OPAL Jet Chamber and their high stretching forces, the holding and positioning of the wires is of special importance. The original concept of crimping had been found to be not reliable enough. Therefore the wires have been soldered twice and wound around a soldering post. Details of the wire suspension system, which will be used with only minor modifications in the final OPAL Jet Chamber, are shown in Fig. 7. All wires are positioned by combs made of dolomite which were machined to a precision of about 10 μm . The sense and potential wires were fed through holes in the aluminium flanges and in the case of the potential wires teflon tubes were used for insulation.

The electrical scheme is shown in Fig. 8. Each potential wire was connected to the HT bus via a 470 Ω resistor which provided a protection of the sense wire in case of sparking and damped possible signal oscillations. The wire to wire cross talk was only slightly increased by adding these resistors.

The signals at both ends of the sense wire were amplified by a factor of 100 by a low noise low impedance amplifier. The parameters of this amplifier, which has no special pulse shaping, can be found in Table 2. The signals were transmitted to the pulse shape digitizers [3] equipped

with a 100 MHz FADC with 6 bit resolution (Siemens SDA 6020) via 37 m long twisted pair cables, where each pair was individually shielded. This type of cable was found to pick up the least amount of radio frequency noise. The receiving amplifier had an additional gain of 8. The total noise determined by integrating the pedestal fluctuations over 200 nsec was typically less than 5×10^3 electrons referred to the amplifier input. This is to be compared with the most probable signal value of 2.3×10^6 electrons. By pulsing the amplifier input with a chamber like pulse the timing accuracy of the whole electronic chain was determined to be 0.3 nsec.

4. EXPERIMENTAL SET-UP

The chamber has been studied both with cosmic ray muons and with a N_2 laser beam. The experimental set-up can be seen in Fig. 9.

For the muon trigger a coincidence between all three scintillation counters was required, which ensures that the particle has traversed 2 cm of lead and 40 cm of iron and which rejects muons with momenta less than 500 MeV/c. Taking into account the momentum spectrum of cosmic rays most triggers correspond to muons of minimum ionisation which allows a study of the particle identification capability of the chamber. By measuring the time difference of the signals at both ends of the trigger counters, the position of the particle along the wire could be determined with $\sigma \sim 2$ cm. The telescope accepted an angle range of $\pm 50^\circ$, which allowed a measurement of the angular dependence of the space charge effect.

This effect, referred to as "saturation effect" has also been studied with a nitrogen laser^{*)}. The laser beam enters the pressure vessel in the direction along the wires and is deflected in the chamber by a tiltable mirror to simulate particle tracks at different angles. However it is difficult to perform an absolute measurement of the saturation effect with this technique because the ionisation behaviour of a particle is different from that of a laser beam, mainly due to the finite width of

*) MOPA 400, Multilaser, Geneva, Switzerland

the latter. Furthermore the nonlinear correlation between the laser intensity and the chamber response has to be corrected for. Another correction has to be made because of the change in reflectivity and geometry in varying the angle of the mirror. Because of all these reasons we have only used the laser for a relative comparison of the different operating conditions [4]. As laser beams will be used for the calibration of the final OPAL detector the tracking accuracy has also been studied with the laser. At 4 bar operation an accuracy of 50 μm was achieved for an ionisation deposit equivalent to minimum ionizing particles.

The gas system provided the desired mixtures of gases. For the studies presented here a premixed gas of Argon (90%) and Methane (10%) was used, to which various amounts (0 to 5%) of isobutane were added by a partial pressure technique. Before filling, the pressure vessel containing the chamber, amplifiers and cables was evacuated to about 5×10^{-4} Torr. By continuous pumping this vacuum was maintained for several days to eliminate impurities outgasing from the various materials. The gas was constantly circulated through an activated copper absorber which reduced the oxygen content to less than 3 ppm and through a 3A° molecular sieve which kept the water content below 50 ppm. The amounts O_2 and H_2O were measured by appropriate instruments^{*)} and the overall quality of the chamber gas was monitored by small-size drift chambers which measured the drift velocity, the gas amplification and the loss of drift-electrons by "attachement" to electro-negative impurities in the gas.

5. EXPERIMENTAL RESULTS

5.1 Choice of operating conditions

The performance of the two chambers regarding space resolution, charge division and ionization measurement was studied using various mixtures of argon, methane and isobutane at 2 and 4 bars absolute

*) (Teledyn Trace Oxygen Analyser Type 317 EX I and SHAW Hygrometer System)

pressure. Table 3 summarizes the voltages, electric fields, gas composition and pressure for the various operating points considered. The operating point 2 corresponds roughly to the 4 bar operation adopted by the JADE experiment. To define an operating point at 2 bar several constraints of the future OPAL detector had to be kept in mind. OPAL will be running with a magnetic field of about 4 kG giving rise to a Lorentz angle which has to be kept small by increasing the drift field. This, however, is limited by the surface field on the wires which can be tolerated. The choice of a drift field of about 700 V/cm seemed a reasonable compromise and the drift velocity plateau was shifted to this value by adding 5% isobutane to the gas. Another requirement was a good charge collection optics which determined the other wire-potentials listed in Table 3.

In the following discussion the analysis and results correspond to operating point 1 unless otherwise stated. A summary of the performance of all operating points will be given in the next section.

5.2 Pulse Shape Studies

The two chambers were also used to investigate the pulse-propagation along the wires and the wire to wire cross talk. For this purpose two potential wires were painted at a small spot with radioactive ^{55}Fe mixed into a silver doped conductive paint. One wire was painted at the middle, the other 50 cm from one end. Although this method allowed studying signal propagation without disturbing the electrostatic properties of the cell, it cannot be recommended for the final detector. After some running time deposits on the neighboring potential wires, near to the painted positions were observed.

In the OPAL detector charge division will be used to measure the coordinate along the wires. This requires the use of amplifiers with a low input impedance which produces an inherent "mismatch" with the wire, especially if a high-resistive wire is used. Therefore a fraction of the signal will be reflected with opposite polarity and will thus modify the

observed signal shape. This was investigated in studying the ^{55}Fe signals for low and high impedance at the wire end. The latter could be obtained in exploiting the feature of the common base amplifier that presents a high input impedance when not powered. By switching on and off the amplifier one could change the polarity of the reflected pulse. The results are shown in Figs. 10 and 11, where the observed pulse shapes are presented together with a schematic explanation. The effects of the "mismatch" are clearly visible. The pulses originating from the ^{55}Fe source at the center of the wires (Fig. 10) are affected identically at both ends, whereas those from the source near to the wire end (Fig. 11) are influenced in an asymmetric way. This effect of "mismatch" results in a deviation of the charge division from a linear behaviour, which will be shown in more detail later.

The radioactive source painted on the potential wires allowed also a study of the wire to wire cross-talk. Fig. 12 shows this effect, for the two source positions. The cross-talk between nearest neighbours amounts to about 7%. The radioactive source was also used to monitor the gas quality by measuring the energy resolution of the Fe^{55} signals.

A detailed pulse shape analysis using the information from the 100 MHz wave-form digitizing electronics was performed for signals from cosmic ray particles. Table 4 summarizes the results of this study. It contains the rise-time (time difference between 10% and 90% levels of the rising edge), the decay time constant (obtained by an exponential fit to 15 FADC samples, starting at the channel with the maximum amplitude). It can be seen that the chamber with the higher resistive wires shows a slower response.

5.3 Drift Time analysis

5.3.1 Determination of the drift time from a FADC pulse

Several algorithms to extract the drift time from the shape of the FADC pulse have been tested :

- a) the timing of the FADC sample with the maximum amplitude
- b) the center of gravity of the pulse
- c) the extrapolation to the pedestal line by means of a cubic spline fit
- d) the reference timing method with various weighting schemes for the FADC samples.

The best accuracy has been obtained with the algorithm d) which is described below.

The reference timing method in which the data pulse is compared to a set of reference pulses shifted in time attempts to exploit all the timing information contained in the pulse shape as digitized by the FADC. First a pulse representative for all data pulses is selected and shifted in steps of 1 nsec by linear interpolation of the amplitudes of each FADC sample. Thus a whole set of reference pulses is created. To determine the drift time of a data pulse a starting value for the timing is taken from its sample with maximum amplitude. Then the precise timing is obtained in comparing the data pulse to the set of reference pulses by minimizing the sum of the weighted quadratic differences.

The timing accuracy of the chamber is studied in two different ways : first by analysing the deviation of the drift time of one wire to a straight line fit through the others and second by the three wire difference $\Delta t = 0.5 \cdot (t_1 + t_3) - t_2$. To evaluate the timing accuracy of a single wire the influence of the others on the width of the distribution is eliminated by applying the correction factor given by error propagation. All accuracies quoted in the following denote the r.m.s. width of the Gaussian fitted to the distribution multiplied by the appropriate correction factor. Averaged over all wires the timing accuracies obtained by the two different methods are equal. A typical distribution of the 3 wire timing difference together with a gaussian fit is shown in Fig. 13.

In Table 5 the timing accuracies obtained with the various algorithms are compared. For the reference timing method the influence of the two

parameters, namely the number of samples involved and their weighting factor, is shown. The best timing accuracy is obtained with the reference timing method using the first two samples of the rising edge of the pulse with equal weights. This means that the timing information is mainly contained in the rising edge of the pulse. Monte Carlo studies [5] simulating the charge collection are in agreement with this conclusion for short drift distances as in the present case. The same Monte Carlo studies and experience with chambers with larger drift distances [6] indicate however that using a larger part of the pulse improves the timing accuracy for longer drift distances.

5.3.2 Resolution of the left-right ambiguity

Fig. 14 shows a typical distribution of the 3 wire difference for all accepted tracks. The two peaks correspond to tracks on either side of the anode plane. The separation of the peaks is in agreement with the expectation from staggering. This distribution demonstrates that the mechanical staggering together with the electrostatic deflection is sufficient to disentangle the left-right ambiguity even with a small number of wires. This is essential for the pattern recognition in the final OPAL detector especially to reconstruct short tracks.

5.3.3 Effects of staggering on the timing accuracy

The timing accuracy obtained from the distributions of the residuals to a straight line fit is plotted as a function of wire number in Fig. 15. For each wire two values corresponding to tracks on either side of the anode plane are displayed. The better timing accuracy is observed for the wires staggered towards the track. This effect is explained by cross-talk from a wire to its neighbours. The wires closer to the track are affected by the cross-talk of their neighbours about 8 ns later than the far wires. Therefore the rising edge of the pulse, which carries most of the timing information is less effected for the wires staggered towards the track. The difference in timing accuracy between the wires near and far from the track is rather constant for all operating conditions.

5.3.4 Dependence of timing accuracy on the drift distance

Fig. 16 shows the timing accuracy as a function of the drift distance. The timing accuracy is worse for tracks very close to anode and cathode planes. This can be explained by a deterioration of charge collection due to field inhomogeneities close to the electrodes, where the leading edge of the pulse is determined by a much reduced number of ionisation clusters.

The contribution of diffusion to the space resolution has been obtained by fitting the function $\sigma^2 = \sigma_0^2 + \delta \cdot x$ for a drift length x between 9 mm and 29 mm which is not influenced by the effects close to the electrodes. The parameters obtained are $\sigma_0 = 97 \pm 5 \mu\text{m}$ and $\delta = 1100 \pm 200 \mu\text{m}^2/\text{cm}$. The results are in good agreement with previous measurements [6]. The statistical errors involved are negligible; the errors quoted account for the uncertainty in the drift velocity and the absolute position of the track. For chambers operating in this accuracy range there are essentially two contributions to σ_0 : ionization fluctuations together with the nonisochronous charge collection and electronic noise. It has already been shown in section 3 that the contribution of the electronic noise is negligible.

5.3.5 Determination of the coordinate along the wire using the timing information

The pulse shapes at both wire ends are very similar at the leading edge as reflections influence mainly the falling edge. Therefore the systematic errors of the drift time determination are likely to cancel out in the difference of the arrival time of the pulse at both ends of the wire. This time difference measures the position of the track along the wire. The observed accuracy of this time difference is 1.3 nsec both for W(Re) and NiCoTi sense wires. Taking into account the different propagation velocities this corresponds to the following relative accuracies $\sigma_Z(\Delta t)$ for the coordinate Z along the wire :

$$\begin{aligned}\sigma_Z(\Delta t) &= (4.5 \pm 1.0)\% \text{ for } 4.5 \text{ m W(Re) wires} \\ \sigma_Z(\Delta t) &= (2.5 \pm 0.6)\% \text{ for } 4.0 \text{ m NiCoTi wires.}\end{aligned}$$

The error takes into account the uncertainty in the propagation velocity which was derived from the observed maximal time difference and the acceptance of the trigger scintillators. The determination of the coordinate along the wire by the time difference is less precise than with the charge division method, which will be discussed in the next section.

5.4 Charge Division Analysis

The coordinate Z along the wires has also been calculated using the charge division method

$$Z = \frac{C_1 Q_1 - C_2 Q_2}{C_1 Q_1 + C_2 Q_2} \cdot \frac{R_w + 2 R_T}{R_w} \cdot \frac{L}{2} \cdot C_3 \quad (1)$$

Q_1 and Q_2 are the charges measured at the left and right end of the wire, respectively, and C_1 and C_2 are the corresponding gain calibration factors. R_w is the resistance of the wire, R_T is the termination resistor at the wire end including the input impedance of the amplifier and L is the length of the wire. The calibration factor C_3 corrects for the small deviations of the resistors from their nominal value and for the capacitors at the amplifier inputs. In principle 2 calibration constants instead of 3 would have been sufficient for the charge division analysis, but because of the dE/dx analysis described in the next section, the overall gains of all wire ends have been calibrated in absolute.

The Z resolution of the chamber has been determined in 3 different ways. In the first method the difference between the Z measurement using the chamber and the track measured using the trigger counters has been determined. This method has the advantage of an external determination of the space coordinate, which allows a determination of the Parameter C_3 , but which has the disadvantage of an additional error due to the trigger counters. In the second method the Z coordinate from one wire was compared to the straight line fit through the others. Finally, the 3-wire method was used. All three methods gave consistent results.

Fig. 17 shows the resolution obtained with the 3 wire method in the middle of the chamber in the range $-10 \text{ cm} \leq Z \leq 10 \text{ cm}$. In Fig. 18 σ_Z is shown as a function of z . In the interval $-75 \text{ cm} \leq Z \leq 75 \text{ cm}$ the resolution is better than 1%. It is somewhat worse towards the ends of the wire.

σ_Z depends also on the integration time of the charge of the pulse as shown in Fig. 19. The Z resolution initially improves with increasing integration time because with increasing collected charge the discrete digitisation steps of the FADC become less important. The best resolution is achieved with an integration time of about 200 nsec for chamber I. For chamber II, which has a slower response the best resolution was obtained with an integration time of 240 nsec. For longer integration times the Z resolution becomes worse because of the decreasing signal to noise ratio. This ratio can however be improved by increasing the gas gain [7].

The linearity of the Z measurement can be seen in Fig. 20 which shows the difference of the Z measurement of the chamber and the trigger counters. It should be noted that the slope of this curve is adjusted in the interval $-75 \text{ cm} \leq Z \leq 75 \text{ cm}$ by the calibration factor C_3 of (1). The observed nonlinearities towards the end of the chamber are due to reflections at the end of the wire, which have been discussed in section 5.2. These nonlinearities which are below 0.5% over the whole wire length can easily be corrected for.

5.5 Ionisation measurement for particle identification

In the following the dE/dx performance of the 8 wire chambers will be discussed and an extrapolation to the OPAL Jet Chamber with 160 ionisation measurements will be made. It should however be underlined that the data come from energetic cosmic ray muons which have a certain momentum spread as discussed in section 3. Therefore the dE/dx resolution obtained with these data is somewhat worse than the intrinsic resolution of the chamber.

The sum of the charges measured at both ends of a wire, integrated over 200 nsec is shown in Fig. 21a). The ratio of the FWHM and the most likely charge is 0.82. This ratio is improved by the following corrections :

- a) According to their track angles the particles traverse different amounts of gas and therefore produce different amounts of charge.
- b) Due to the staggering of the wires more electric fieldlines end on the sense wire near to the track compared to the sense wire on the other side of the potential wire plane. Because of this the near wires collect about 15% more charge than the far wires.
- c) The biggest correction comes from the saturation effect. For tracks which are perpendicular to the sense wires all ionisation clusters arrive at a small spot of the wire. The ions of the first avalanches shield the electric field near the sense wire and the electrons arriving later experience less gas amplification. As diffusion increases the spot size the saturation effect decreases with increasing drift path. This is clearly shown in Fig. 22 which shows the charge as a function of the track angle for short and long drift distances.

The charge distribution for one wire after these corrections is shown in Fig. 21b). The ratio FWHM/most likely value has improved to 0.71. In this analysis no correction for cross talk has been applied, which would further reduce this ratio.

From the 8 measurements of the energy loss of a particle in the chamber a "truncated mean" has been calculated in averaging over the 5 smallest charges of the 8 wires. This distribution together with a Gaussian fit is shown in Fig. 23. The fit gives $\sigma/\text{mean charge} = (12.7 \pm 0.2)\%$ which is taken as the dE/dx resolution for 8 wires. Assuming a scaling as $n^{-0.46}$, which takes the correlation between n measurements into account [8] the expected dE/dx resolution for 160 wires in the OPAL detector is 3.2%.

5.6 Summary of results

Table 6 summarizes the results obtained for the two chambers, using minimum ionizing muons from cosmic radiation. The operating points referred to in the first column are those given in detail in Table 3. Chamber II was run at a higher gas gain in order to have a sufficiently large pulse amplitude at the far wire end. Because of the higher wire resistivity the charges divided in a more asymmetric way compared to chamber I. The tracking resolution σ_x and the charge division resolution σ_Z/Z are averaged over the 8 anode wires. The values of σ_x were obtained for drift distances between 5 mm and 28 mm and those of σ_Z/Z for the central region ($|Z| < 75$ cm) of the chambers. The saturation correction to the charge measurement is given separately for short and long drift distances. The resolution of the ionisation measurement, given by the spread of the truncated mean charge of 5 out of the 8 anode wires, corrected for track angle and saturation is listed in the last column.

The results can be summarized as follows :

- a) Both chambers have reached similar tracking accuracies of the order of 100 μ m at 4 bar of pressure and for an average drift distance of 1.5 cm. Because of the lower cluster density at 2 bar pressure this resolution becomes worse by about 30% - 40%.
- b) Chamber I has reached a charge division resolution of $\sigma_Z/Z \sim 1\%$ in the central region - it becomes 20% - 30% worse towards the ends. The resolutions are about the same for both gas pressures and the small differences are due to the slightly different gas gains. Because of the higher resistivity of the NiCoTi wires and the higher gain, Chamber II obtained a Z-resolution of about 0.8%.
- c) By extrapolating the dE/dx resolution, observed in these 8-wire chambers, to the 160 wires of the OPAL Jet chamber a satisfactory particle identification can be expected.

6. CONCLUSION

This investigation has demonstrated that it is possible to find a successful mechanical solution for a 4.5 m long Jet Chamber with a safe electrostatic behaviour and to operate it at pressures between 2 and 4 bar. A good performance in all relevant characteristics has been reached, namely the tracking accuracy, the charge division resolution and the dE/dx resolution with acceptable saturation corrections.

The favoured solution is the one of chamber I with 25 μm W(Re) sense wires because of its safe mechanical and electrostatic characteristics. Despite the low electrical resistivity of the wire this chamber yields a satisfactory Z resolution.

The solution of chamber II with NiCoTi sense and potential wires presents mechanical and electrostatic problems. In order to keep the wire deflection within tolerable limits the Cu-Be wires have to be stretched close to their elasticity limit. This configuration can therefore not be recommended for chambers of this length. A solution using only NiCoTi wires would avoid the electrostatic problems. It has to be discarded, however, for a large detector such as the OPAL Central Detector due to the serious difficulties encountered in soldering NiCoTi wires.

Finally the iterative electrostatic calculation was successful in predicting the electrostatic behaviour of the two chambers. This technique is quite general and should be applied in the design of any chamber, where the electrostatic deflection become critical.

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TABLE CAPTIONS

Table 1 Mechanical parameters of the chambers.

Table 2 Parameters of the electronics.

Table 3 List of operating points.

Table 4 Pulse shapes of the chamber signals for the different operating conditions.

Table 5 Comparison of the timing accuracies obtained with different algorithms.

Table 6 Summary of the results for the different operating points. The Z resolution σ_Z/Z is an average over all wires in the range $-75 \text{ cm} \leq Z \leq 75 \text{ cm}$. The tracking resolution σ_x was determined with the reference pulse timing methode excluding the regions (5 mm) near the wire planes. The saturation effect is defined as (charge 45° - charge 0°)/charge 0° . The dE/dx resolution is given as (width σ /mean value) of the truncated mean charge distribution.

TABLE 1

PARAMETER	CHAMBER I	CHAMBER II
Length of anode and potential wire	4568 mm	4072 mm
Length of cathode wire	4340 mm	3890 mm
Spacing of anode wire to potential wire	5 mm	5 mm
Spacing between cathode wires	2.5 mm	2.5 mm
Diameter of anode wire	25 μm	30 μm
Diameter of potential wire	100 μm	175 μm
Diameter of cathode wire	100 μm	100 μm
Material of anode wire	W(Re)	NiCoTi
Material of potential wire	Cu-Be	NiCoTi
Material of cathode wire	Cu-Be	Cu-Be
Stretching force of anode wire	1.0 N	0.9 N
Stretching force of potential wire	6.7 N	30.2 N
Stretching force of cathode wire	6.1 N	7.4 N
Mechanical staggering of anode wire	$\pm 100 \mu\text{m}$	$\pm 100 \mu\text{m}$
Gravitational sag of anode plane	245 μm	131 μm
Gravitational sag of cathode plane	245 μm	163 μm
Gap anode - cathode	33 mm	33 mm
Gap cathode - mirror	33 mm	33 mm
Positioning error of the anode wire	$\leq 20 \mu\text{m}$	$\leq 20 \mu\text{m}$
Error in location of cathode plane with respect to anode plane	$\leq 50 \mu\text{m}$	$\leq 50 \mu\text{m}$
Resistivity of the anode wires	202 Ω/m	1305 Ω/m

TABLE 2

<u>PREAMPLIFIER VV36</u>	
Type	Common base input, differential output
Input impedance	40 Ω
Gain (at 100 Ω)	100
Rise and fall time response	$\sim 6 \text{ nsec}$
Noise	$\sim 2000 \text{ electrons r.m.s.}$
Power consumption	156 mW
<u>CABLE</u>	
Type	twisted pair, each pair individually shielded (CABELTEL ref. No. 71757)
Impedance	100 Ω
Length	37 m
<u>FLASH ADC</u>	
Gain of differential receiver	8
FADC chip	Siemens SDA 6020
Sampling frequency	100 MHz
Range	6 bit

TABLE 3

OPERATING POINT	CHAMBER	U_{POT} [kV]	U_{CATH} [kV]	U_{MIRROR} [kV]	E_{DRIFT} [V/cm]	ELECTROSTATIC DEFLECTION OF SENSE WIRES (calculations) [μm]	$E_{\text{ANODE WIRE}}$ [kV/cm]	$E_{\text{POT WIRE}}$ [kV/cm]	$E_{\text{CATH WIRE}}$ [kV/cm]	GAS MIXTURE [%]			PRESSURE [bar]	AVERAGE DRIFT VELOCITY [$\mu\text{m/ns}$]
										Ar	CH ₄	IC ₄ H ₁₀		
1	I	-2.7	-5.19	-1.4	910	± 97	322	22.8	15.4	90.0	10.0		3.8	53 ± 2
2	I	-2.5	-5.19	-1.4	940	± 130	308	17.5	15.7	87.3	9.7	3.0	3.8	50 ± 2
3	I	-2.0	-3.95	-1.3	700	± 43	242	15.8	11.4	85.5	9.5	5.0	1.9	50 ± 2
4	I	-2.1	-4.1	-1.3	720	± 47	252	17.2	12.0	90.0	10.0		1.9	44 ± 2
5	II	-2.9	-5.41	-2.0	940	± 70	295	16.8	13.5	87.3	9.7	3.0	4.0	50 ± 2
6	II	-2.25	-4.12	-1.7	710	± 30	228	13.7	10.0	85.5	9.5	5.0	2.0	53 ± 2

TABLE 4

OPERATING POINT	CHAMBER	RISE TIME [ns]	DECAY TIME [ns]
1	I	20.2	81
2	I	19.1	81
3	I	19.8	78
4	I	21.5	71
5	II	38.5	98
6	II	38.0	86

TABLE 5

TIMING METHOD	σ [ns]	σ [μ m]
a) timing of FADC bin with maximum amplitude	5.1	255
b) center of gravity (average over 200 ns)	4.0	200
c) spline fit extrapolation to baseline	3.0	150
d) reference timing method		
i) equal weights		
first 2 FADC samples	2.0	100
first 3 FADC samples	2.3	115
first 4 FADC samples	2.4	120
first 5 FADC samples	2.6	130
first 6 FADC samples	2.8	140
ii) non-equal weights		
weight factor 9, 6, 3, 2, 6 * 1	2.3	115
weight factor 5, 4, 2, 2 * 1	2.3	115
weight factor 20, 5, 3 * 1	2.2	110

TABLE 6

OPERATING POINT	CHAMBER	PRESSURE [bar]	MOST LIKELY AMPLITUDE [counts]	MOST LIKELY CHARGE [counts]	TRUNCATED MEAN [corrected counts]	TRACKING RESOLUTION σ_x [ns] [μm]	CHARGE DIVISION RESOLUTION σ_z/z [%]	SATURATION EFFECT [%] 0-6mm DRIFT 6-30mm DRIFT	dE/dx RESOLUTION [%]
1	I	3.8	14.5 $\pm$ 1	180 $\pm$ 5	161 $\pm$ 1	2.0 106 $\pm$ 5	1.0 $\pm$ 0.05	31 $\pm$ 2 19 $\pm$ 2	12.7 $\pm$ 0.2
2	I	3.8	14.5 $\pm$ 1	196 $\pm$ 8	183 $\pm$ 1	2.0 100 $\pm$ 5	1.0 $\pm$ 0.05	38 $\pm$ 5 26 $\pm$ 2	12.2 $\pm$ 0.1
3	I	1.9	13.5 $\pm$ 1	176 $\pm$ 5	160 $\pm$ 1	2.6 130 $\pm$ 7	1.1 $\pm$ 0.05	30 $\pm$ 3 21 $\pm$ 2	14.7 $\pm$ 0.2
4	I	1.9	15.5 $\pm$ 1	200 $\pm$ 8	181 $\pm$ 1	3.1 136 $\pm$ 7	0.9 $\pm$ 0.05	26 $\pm$ 3 17 $\pm$ 2	16.1 $\pm$ 0.2
5	II	4.0	12.0 $\pm$ 1	288 $\pm$ 10	248 $\pm$ 1	2.2 111 $\pm$ 6	0.8 $\pm$ 0.05	47 $\pm$ 5 32 $\pm$ 3	14.4 $\pm$ 0.4
6	II	2.0	12.0 $\pm$ 1	264 $\pm$ 10	219 $\pm$ 1	2.5 132 $\pm$ 7	0.75 $\pm$ 0.05	28 $\pm$ 3 20 $\pm$ 2	15.9 $\pm$ 0.5

- Fig. 12 Cross talk from one wire to the next (chamber I).
a) middle position of Fe^{55} source,
b) source positionned 50 cm from one wire end, signals seen at the "near" wire end.
- Fig. 13 3 wire timing difference $\Delta t = 0.5 \cdot (t_1 + t_3) - t_2$
- Fig. 14 3 wire timing difference Δt for tracks at both sides of the anode plane.
- Fig. 15 Timing accuracy. The circles correspond to measurements where the wire was staggered towards the track, the crosses to staggering away from the track.
- Fig. 16 Timing accuracy as a function of drift time.
- Fig. 17 Z resolution in the middle of the chamber ($|Z| < 10$ cm).
- Fig. 18 Z resolution as a function of Z.
- Fig. 19 Z resolution as a function of the integration time.
- Fig. 20 Difference ΔZ between the Z measurements of the trigger counter and of the chamber.
- Fig. 21 Charge as measured on one wire a) before and b) after corrections (see text).
- Fig. 22 Truncated mean charge corrected for the sample thickness as a function of the track angle θ for 0 - 6 mm drift path (dots) and for 6 - 30 mm drift path (crosses).
 $\theta = 0^\circ$ corresponds to tracks perpendicular to the wire.
- Fig. 23 Truncated mean charge calculated from the 5 smallest of the 8 charge measurements together with a gaussian fit (mean = 148.2 ± 0.2 , $\sigma = 18.8 \pm 0.2$)

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

a)

b)

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

FIG. 12

FIG. 13

FIG. 14

FIG. 15

FIG. 16

FIG. 17

FIG. 18

FIG. 19

FIG. 20

FIG. 21

FIG. 22

FIG. 23