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A SYSTEM OF TWO-DIMENSIONAL DRIFT CHAMBERS
WITH PRINTED-BOARD CATHODES AND FLAT SOLENOIDAL DELAY LINES

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ABSTRACT

In this paper we describe the structure and performance of a system of 34 drift chambers, which has been in operation at the CERN Intersecting Storage Rings (ISR) since August 1977 in the experiment R209, $p + p \rightarrow \mu^+ + \mu^- + X$. The field shaping of the drift cell has been obtained by means of printed-board cathodes; the read-out is two-dimensional by means of 83 cm long flat solenoidal delay lines, wound around 200 μm thick vetronite strips.

We report here some results on the main operating features, like efficiency, rate capability, space resolution (wires = 250 μm ; delay lines = 1.8-4 mm) at a test beam and under ISR running conditions.

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1. INTRODUCTION

In this paper we describe the structure and performance of a system of drift chambers, developed and built for the experiment R209, which has been running at the CERN ISR since 1977. This experiment, performed by the CERN-Frascati-Harvard-MIT-Naples-Pisa Collaboration, is studying the reaction $p + p \rightarrow \mu^+ + \mu^- + \text{hadrons}$. The apparatus consists of a big magnetic spectrometer spanning the angular range 15° - 105° , with respect to the bisector of the beams, for $\mu^+\mu^-$ detection and a $\sim 4\pi$ hadron detector. Both make use of counter hodoscopes and drift-chamber telescopes.

The large chambers (their dimensions are up to $6 \times 3 \text{ m}^2$) of the μ spectrometer are described elsewhere¹⁾; the description of the drift chambers (typical size $40 \times 20 \text{ cm}^2$) forming the "central box" for the tracking of the particle paths close to the interaction vertex can be found in another paper²⁾.

The chambers we are concerned with here are part of the hadron detector and are arranged in two telescopes of a total of 34 units. They cover the angular range between 1° and $\sim 30^\circ$ with respect to the downstream beam in the region not covered by the magnetic spectrometer. Each plane of drift chambers has a sensitive area of $83 \times 83 \text{ cm}^2$ and a two-dimensional read-out by means of sense wires and delay lines. To solve left-right ambiguity and to handle easily the very high ISR rate (10^6 events/s) and multiplicity (10-20 tracks/interaction) each plane is paired to a plane with wires staggered by half a cell, 40 mm apart and without delay lines.

In the following we describe the two-dimensional chambers.

2. DESIGN OF THE CHAMBERS

The mechanics of the chambers has been designed to meet some general requirements: i) the chambers have to be arranged in planes of measurement around and orthogonal to the ISR pipe; ii) the sensitive volume of the chambers has to be as close as possible to the pipe; iii) the telescope must be built as far as possible in a modular manner; iv) heavy frames on particle paths must be avoided.

Although it was not possible to achieve a complete modularity, 32 out of 34 chambers have the same shape and 24 also the same dimensions.

To permit good spatial resolution and time-space linearity we have preferred a shaped field configuration of the drift cell. To avoid the need for heavy frames and to simplify construction and maintenance problems connected with the use of a large number of field shaping wires, we decided on a different approach based on large printed-board cathodes. A perspective view of a module is shown in Fig. 1. It is L-shaped and the wires are parallel to the longest side (83 cm). The L-shape of these chambers has been made possible by the use of self-supporting cathode planes, constituted by a 10 mm thick acrylic foam slab of 31 kg/m^3 specific gravity, sandwiched between two 0.2 mm FR 4 vetronite sheets. The inner one supports a pattern of parallel golded copper strips, i.e. the field-shaping conductors, $0.17 \text{ }\mu\text{m}$ thick, 1 mm wide and 2.1 mm apart. The outer sheet provides an electromagnetic shield by means of an additional copper layer at ground potential. This self-supporting structure is terminated by vetronite frames, 5 mm thick at the inner edges. The adhesives are epoxy resins, namely CIBA GEIGY AW 106 and AY 103, used respectively with HV 953V and HY 956 hardeners. The total thickness of the chamber is 0.32 g/cm^2 . Gas tightness is assured by a 2 mm neoprene 45° shore O-ring.

As indicated in Fig. 2, the drift half cell is 23.25 mm wide and the gap from cathode to cathode is 12 mm. Sense and field wires (gold-plated tungsten) are 20 and $50 \text{ }\mu\text{m}$ in diameter and are stretched between cards fixed to the vetronite frames, with a mechanical tension of 50 g and 150 g, respectively. In order to prevent the wires from slipping off from welding spots, a two-point soldering was adopted. The same cards supported four reference pins for the geometrical survey of the chambers.

Tests on prototype chambers showed that the cells confined by the vetronite frames were noisier than the inner ones. By covering the internal vetronite surface with a conductive paint, in electrical connection with the nearest strip, at negative high voltage, we eliminated this drawback thoroughly.

The field shapers receive their voltages from a plug-in voltage divider (see Fig. 1), built of seven $1.00 \pm 0.01 \text{ M}\Omega$ resistors, through eight distribution strips printed on the other side of the vetronite sheet, perpendicular to the cathodic strips. The field wires are connected all together to the negative high voltage power supply by means of a $5 \text{ M}\Omega$ resistor, acting as current limiter in case of wire breaking.

3. DELAY-LINE CHARACTERISTICS

The delay-line design had to satisfy a certain number of constraints, of geometrical or electrical nature:

- i) The shaping field of the cell had to receive negligible perturbation.
- ii) The distance from the sense wire had to be high enough to avoid electric sparks and to leave nearly undisturbed the field around the sense wire. On the other hand this distance had to be small enough to ensure good coupling efficiency.
- iii) Owing to the rather large number of cells to be read, the construction had to be simple; moreover the total thickness of the line had to be minimized, being in the path of particles.
- iv) The sum of the maximum drift time and of the total propagation time on the line had to be lower than $1.5 \mu\text{s}$, the time span of the time-to-digital converter (TDC) system. This means that the available time interval for the line was $\sim 900 \text{ ns}$ which, for an 83 cm length, corresponds to a maximum specific delay of 11 ns/cm .
- v) To achieve a good spatial resolution we needed a high specific delay (with the previous limitations), good rise-time and limited attenuation, which means low ohmic resistance and high characteristic impedance Z_0 .

To find a compromise among the previous requirements, often incompatible, we investigated the performance of flat solenoidal delay lines glued onto the printed cathodic plane which fulfilled requirements (i) and (ii) in a better way than the conventional cylindrical ones.

Further constraints were: a) the distance between the strips of the cathode plane (2.1 mm), limiting the line width to ~ 5 mm; b) the distance between the cathodic plane and the wire (6 mm), limiting the line thickness, to ~ 1.5 mm. After many tests, we fixed on the final design shown in Fig. 3. An 80 μm enamelled copper wire is wound, with a 100 μm pitch on a very thin vetronite strip, 200 μm thick and 4.5 mm wide. The strip has one metallized side (35 μm of copper) and is covered by a heat-shrinkable polyethylene tubing, with high resistivity and low dielectric losses.

The external dimensions of the line are 5.2 mm in width and 1.4 mm in height. Each line is glued onto one of the printed-board cathodic planes, on the two earthed strips just below the corresponding sense wire, as shown in Fig. 3.

Outside the chamber, the specific delay τ and the characteristic impedance Z_0 are satisfactorily described by the simple formulae derived from the "sheath helix" model^{3,4)}:

$$\tau \approx \sqrt{\epsilon\mu} \cot \psi = \frac{2\sqrt{\epsilon_r} w}{cp} ; \quad Z_0 \approx \frac{a}{p} \sqrt{\mu/\epsilon}$$

where w , p and ψ are width, pitch and pitch angle of the helix; a is the distance between the helix and the internal conductor; $\epsilon = \epsilon_0\epsilon_r$ and μ are the dielectric constant and the magnetic permeability of the insulator, respectively; c is the velocity of light in vacuum.

The measured specific delay and characteristic impedance are also consistent with the first approximation formulae

$$\tau = \sqrt{LC} , \quad Z_0 = \sqrt{L/C} ,$$

where, with our geometry, $L = 6.3 \mu\text{H}/\text{cm}$ and $C = 5.1 \text{ pF}/\text{cm}$. The specific resistance, relevant for the signal attenuation, is $R = 4.1 \Omega/\text{cm}$. The values of previous parameters, measured for lines outside the chambers, are:

$$\tau = 5.7 \text{ ns}/\text{cm} ; \quad Z_0 = 1110 \Omega .$$

As expected, when the lines are glued onto the two earthed cathodic strips, the specific delay rises in a relevant way. This is mainly due to the fact that the specific capacitance C strongly increases, whilst the specific inductance L remains practically undisturbed.

The actual values we obtain in the chamber are finally

$$\tau \approx 10.2 \text{ ns/cm} , \quad Z_0 \approx 680 \, \Omega .$$

The numbers quoted are typical values. As a matter of fact there is a certain spread in these numbers, as we will discuss later, owing to the somewhat delicate construction process (the winding on a thin and long support and, mostly, the gluing on the cathodic strips). We anticipate here that the r.m.s. value of the specific delay distribution of the full sample is 0.7 ns/cm, which corresponds to the 7% of the average τ .

4. CHAMBER ELECTRONICS

Signals from sense wires are sent, via a 0.45 m long RG 178 coaxial cable, to a multipin coaxial connector fixed on the chamber. The delay lines, read at both ends to eliminate multiparticle ambiguity, are first terminated by their characteristic impedance and are matched via an emitter follower to the RG 178 coaxial cable which, as for the sense wires, carries the signals to the output multipin connector. Power is supplied to the emitter follower through the output cables.

Owing to possible radiation damage and to the difficult access which does not permit the substitution of a broken transistor if it is necessary, without dismounting the chamber, the four delay line ends facing the ISR pipe are terminated by little pulse transformers, built by toroidal ferrite rings ($\phi_{\text{int}} = 4 \text{ mm}$, $\phi_{\text{ext}} = 6 \text{ mm}$, $h = 2 \text{ mm}$), instead of by the emitter follower. The outputs of the transformers are connected to the coaxial output connector by RG 178 cables, having a 50 cm extra length, which run embedded in the acrylic foam along two sides of the frame.

Signals from sense wires and delay lines are fed into the amplifiers via GO 2223 coaxial cables 3.5 m long. The amplified signals are sent, via 60 m long RG 58 cables, to the discriminator and to the TDC system. Amplifiers, discriminators and TDCs are all organized in 8-channel cards. The TDC system has been developed at Nevis Laboratories (Columbia University)⁵⁾ and uses a common stop signal provided by the trigger of the experiment, conveniently delayed: with this solution, a big number of delay boxes, one on each channel, is avoided. To handle multiparticle events without loss of signals, each TDC module accepts up to 14 pulses per trigger arbitrarily distributed among the eight channels. The time resolution is 1.5 ns, while the time span is 1.5 μ s.

4. PERFORMANCES OF THE CHAMBERS AT THE TEST BEAM

Some chambers were extensively tested initially at the CERN cyclotron, and then at the CERN Proton Synchrotron using a 5 GeV π^- beam. Beam size and zero-time were defined by different coincidences among 8 scintillators of various dimensions, which permitted a minimum beam size of 1×1 mm². For some tests, in order to define a track, two small drift chambers, built in the standard way with wire cathode planes, were used. The chamber to be tested was placed on a support capable of remote-controlled horizontal and vertical movements. Both amplifiers and discriminators, as well as cable types and lengths, were the same as subsequently used in the actual experiment. Only the TDCs were different, but they had a similar bin width.

Various mixtures of argon (60-75%) and isobutane with a small addition of methylal were used. The results reported in this section refer to the 69% argon, 28% isobutane and 3% methylal mixture. Efficiency, space-time relation, and resolution were analysed for several chambers and for different cells of the same chamber, and some results, for sense wires and delay lines, are reported in the following.

4.1 Sense wires

Figure 4 shows typical high-voltage plateaux for two different gas mixtures and for two discriminator thresholds. As can be seen, changing the argon content

from 69% to 64% the plateau shifts by 50 V toward higher tensions, while the shift is of 30 V if the discriminator threshold goes from 10 to 20 mV, with a gain of 90. If we change the negative high voltage from -2800 V to -3000 V, the plateau shifts by 30 V, in the opposite direction, toward lower tensions.

The space-time relation, at -2800 and +1700 V, is shown in Fig. 5. The slope, that is the inverse of the drift velocity, is 19.71 ± 0.13 ns/mm.

The drift velocity shows no sensible variations if we vary the negative voltage between -2600 and -3000 V, and the positive voltage between the limits of the plateau. No appreciable differences in the space-time relations were found for tracks inclined up to 25° .

In Fig. 5 the efficiency, with the standard gas mixture 69% argon, 28% isobutane, 3% methylal as a function of the distance from the sense wire, is also shown. As can be seen, the efficiency is greater than 99% everywhere. The width of the transition region across the field wire, where the sum of the efficiencies of the two adjacent drift cells has to be considered, is mainly due to the finite width of the beam.

Values of the efficiency versus rate are reported in Fig. 6. The efficiency remains practically 1, if we increase the incident particle rate up to a maximum of 2×10^3 particles per second and per mm of sense wire length, and it has still a value of 90% at a rate of 10^4 particles/(s·mm). Note that, owing to the beam size, the last number was measured under an integral flux of 7×10^5 particles/s in an area of 4×8 cm² contained in one cell.

No loss of efficiency, or variation of drift velocity, was found near the edges of the chambers parallel to the wires (the outside wires are field wires and are placed at 1.5 mm from the vetronite). Near the edges where the wires enter the frame a slight loss of efficiency has been observed, starting about 5 mm from the frame.

The spatial resolution was measured coupling, close to each other, two chambers with parallel wires and measuring the differences, $x_1 - x_2$, of the distances from two associated wires of the same track perpendicular to the wire planes.

In Fig. 7 the distribution of the deviation of $x_1 - x_2$ from the mean is plotted. The r.m.s. value of the distribution divided by $\sqrt{2}$ can be assumed as an over-estimate of the resolution (assumed equal) of the two sense wires and associated electronics. From the histogram one gets $\sigma = 0.24$ mm. In this value of σ there is a contribution from the multiple scattering of the order of ten microns. Measurements for several positions in the drift space and for several cells gave similar results, so a value of 0.25 mm has been assumed as the spatial resolution for perpendicular tracks of minimum ionizing particles.

4.2 Delay lines

As far as the delay lines are concerned, at the test beam we investigated mainly the following characteristics: i) efficiency; ii) space-time linearity; iii) space resolution; iv) attenuation.

We studied efficiency versus discriminator threshold for various lines, and the result was that noise put a lower limit of ~ 5 mV, whilst at 25-30 mV, with an amplifier gain of 90, a noticeable decrease in efficiency began to appear. The best compromise between noise rejection and time resolution was obtained by setting the various thresholds in the 9-12 mV range. Owing to the higher pulse amplitudes of the sense wires, their thresholds were fixed at 15 mV with a similar procedure.

To investigate the space-time relation we scanned longitudinally a rather large sample of the delay lines, recording the time between line and sense-wire pulses. As shown in the typical result of Fig. 8, we obtained a very good linearity along the whole length for all the examined lines. On the other hand, for the reasons outlined in Section 3, the specific delay was not the same for all the lines, but was distributed around a mean value of 10.2 ns/cm with $\sigma = 0.7$ ns/cm. These numbers were confirmed later on the full set of lines, at the ISR.

Another interesting performance of the lines was their space resolution and its dependence on the longitudinal position of the beam. These measurements were performed, defining a $1 \times 1 \text{ mm}^2$ beam, scanning along the line, and recording the resulting width of time distribution at each end. Gas mixture, high voltages, thresholds and amplification were fixed at the values previously decided. In Fig. 8 we show a typical result obtained with this procedure: the resolution remains practically independent of the position up to 50 cm, at a value of $\sigma \approx 1.8\text{-}2.0 \text{ mm}$, and then begins to increase with the distance, doubling when the pulse has to propagate along the full delay-line length, 83 cm. For the experiment at the ISR, it was convenient to choose the lower of the two readings obtained from the line ends, instead of their average.

The attenuation, which is responsible for the space dependence of resolution, was investigated, recording, for each position, the output pulse height. In Fig. 9 the peak abscissa of the rather broad distributions, in which the typical tail at large values is present, is plotted, on a logarithmic scale. As can be seen from the figure, the attenuation follows an exponential law, with an amplitude decrease of a factor of 2.2 over the full distance of 83 cm.

5. THE CHAMBERS AT THE ISR

Because of the high rate of particles, due both to background and beam-beam interactions, and because of the long exposure time, the ISR environment is a very severe one for wire chambers. A typical counting rate of all the wires of a chamber is shown in Fig. 10. As can be seen with a luminosity of $1.2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, the rate of 83 cm long wires varies between $\sim 50 \text{ kHz}$ and $\sim 180 \text{ kHz}$, depending on the wire position.

At the beginning, the chambers showed a tendency to become noisier and less efficient after two or three months of running at the ISR. Actions were then taken to improve the working conditions, mainly to lower the voltages of the chambers:

- i) the amplifiers were modified to gain a factor of 2 in amplification (from $\times 90$ to $\times 180$);
- ii) the argon-isobutane-methylal gas mixture was replaced by an argon (60%) and ethane (40%) one, for which a lower electric field is sufficient to get a saturated drift velocity⁶⁾.

These modifications permitted a substantial reduction in positive and negative high voltages, from +1700 V to +1500 V and from -2800 V to -2200 V: under these conditions the long term behaviour of the chambers was satisfactory.

The argon-ethane mixture has other advantages over the argon-isobutane-methylal mixture: i) the drift velocity depends slightly on the percentages of the two components; ii) no agent, like methylal, is needed to inhibit polymer deposition on the cathodes⁷⁾; iii) it is better suited for high rates because of the larger ion mobility of ethane.

Figure 11 shows a typical drift-time spectrum obtained by operating the chamber with the argon-ethane mixture at -2200 V and +1500 V, with a 15 mV discriminator threshold. The spectrum has the correct flat-top which is expected under uniform illumination if drift velocity is saturated and if efficiency does not depend on the distance from the sense wire. The level of off-time signals is not due to chamber or amplifier noise, but is characteristic of the high intersection rate and radiation background of the ISR. It is observed in all the chambers and depends strongly on beam conditions and cell positions.

The rejection of spurious hits, i.e. hits not connected with the trigger but belonging to a previous or to a following interaction, is greatly simplified by the multihit capability of the TDC system and by the use of staggered cells. In particular, after the obvious request that measured times have to be contained between zero and the maximum drift-time, we apply experimentally determined cuts on the sum or on the difference of the two staggered cell readings, and this simplifies pattern recognition already at the TDC decoding stage. Figure 12 demonstrates this simple method: for tracks like A, the constant quantity (i.e. independent of the incidence point) is $t_1 - t_2 = T$, and becomes $t_1 + t_2 = T$ or $t_1 - t_2 = -T$ for

tracks of type B or C, respectively. It is clear that two signals coming from an off-time event simulate a track with a "wrong" angle, not coming from the interaction region, and are then rejected. The value of T depends on cell position and is experimentally determined for each cell by means of spectra like the one shown in Fig. 13, where the sum of staggered wire readings for perpendicular tracks is histogrammed. In this case, T is equal to the maximum drift-time and its value turns out to be equal to 467 ns, in agreement with the drift-time spectrum shown in Fig. 11: this time interval corresponds to a drift velocity of 20.1 ns/mm. We may add here that dividing the r.m.s. of the spectrum by $\sqrt{2}$ we obtain a space resolution of 230 μm , consistent with test-beam measurement.

In order to monitor the long-term stability of the chambers, we defined "signal" the number of hits obtained from drift-time spectra like the one shown in Fig. 11, after having subtracted the off-time events level. We then calculate the signal to triggers ratio, and check, for all the cells, whether this relative efficiency is constant in time, and whether chambers of similar geometry give consistent absolute values. During the ISR running, the dependence of relative efficiency as a function of high voltages or discriminator thresholds was periodically measured, using an inclusive beam-beam trigger.

An example of the dependence of this "efficiency" on the sense-wire voltage, showing a clear plateau for $+HV > 1400$ is given in Fig. 14. All the chambers have operated at $-HV = 2200$ V, with positive tensions ranging between +1500 and +1600 V; sense-wire thresholds have been fixed at 15 mV, whilst delay lines were fixed at 9-12 mV.

The delay-lines setting was decided and then periodically checked by monitoring the efficiency of each line relative to the associated sense wire. We adopted a method which takes into account the fact that, to solve multiparticle ambiguity, pulses at both ends of each delay line are requested. A "triplet" was defined as an event producing signals on a sense wire and at both ends of the associated delay line, satisfying the following time relation

$$t_{d1} + t_{d2} - 2t_s = T_L \pm 3\Delta T_L ,$$

where t_{d1} and t_{d2} are the times measured at each delay line end, t_s is the drift time, T_L is the mean value of the propagation time along the whole line ("delay line length"), and ΔT_L is its standard deviation. The ratio of the number of triplets to the number of on-time hits on the sense wire is adopted as a monitor of the efficiency of the delay line.

Other quantities frequently checked are the delay lengths T_L and their widths, since changes in a delay length or in its σ are monitors of variations in pulse heights and of relative changes of the zero times of time spectra.

An example of delay-line length distribution is given in Fig. 15. The length of the line is 563 TDC bins, i.e. 844 ns, and its standard deviation is ≤ 3 TDC bins (~ 3.7 mm). The last number is consistent with test-beam measurement if we consider that each T_L is calculated by summing the information of both line ends, accepting tracks along the whole length of the line. At the track-fitting stage, the errors on the coordinate measured by the delay lines are slightly larger than their resolution (~ 3 mm instead of ~ 2 mm), as can be seen from the example in Fig. 16, which shows the distance between points measured by a particular delay line and the corresponding tracks, fitted by requiring information from at least four sense wires on the same coordinate provided by the line. The width of this kind of residual is determined mainly by line resolution, but also by possible local non-linearities, and by geometrical or zero-time uncertainties.

In Fig. 17 a reconstructed event is shown, in two projections, with four tracks in one of the two telescopes -- the one nearer to the intersection region. Full and dashed segments represent planes with and without delay lines, respectively, while asterisks between them represent space points averaged from the two staggered chambers; dashed and dotted lines are the axes of the two beams. Three tracks are not recorded by the first chamber plane because the particle trajectories are inside the vacuum pipe.

The chambers have been in operation at the ISR for more than two years, under a high radiation level (~ 1 MHz per chamber); with an argon-ethane mixture and increased signal amplification they behaved satisfactorily over periods of the order of a year, requiring only some threshold or positive high voltage adjustment to maintain high efficiencies. During the long annual shutdowns, we have changed all sense wires to reproduce the initial setting up.

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Figure captions

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