LHCb-2001-011
Outer Tracker

Beam tests of LHCb Outer Tracker prototypes in 2000

I. Gouz, B. Hommels, G.W. van Apeldoorn
NIKHEF
Amsterdam
February 6, 2001

Abstract

This note presents the results of beam tests of LHCb Outer Tracker prototype modules performed at CERN in 2000. The properties of Ar/CF4/CO2 gas mixtures were studied and 2m long straw tubes of different designs were tested.

1 Introduction

This note describes the beam tests of LHCb Outer Tracker prototype modules performed at CERN in 2000. The tests were conducted at the T7 beam of the CERN PS accelerator in two periods, 3-21 May and 25 September - 8 October.

The results of the previous testbeam studies, made in 1998 and 1999, are described in [1]. In 2000, we used the same PS T7 beam area, the same readout electronics and data acquisition system, so in this note we do not describe them, referring the reader to [1].

The major DAQ problems, described in [1], were solved by the beginning of the 2000 run, and this gave us a possibility to take a significant amount of data and perform high-statistics studies of the chambers' performance[1].

There were two main questions addressed in the beam tests in 2000:

- the properties of the drift cell with our standard geometry (d_{tube}=5 mm, d_{wire}=25 μm) at gas mixtures based on Ar, CF_4 and CO_2;
- the performance of "half-scale" 2m long prototypes of the final detector module.

2 Prototypes

The following prototypes were tested at the PS beam in 2000:

- four short straw chambers (30 cm length), made at NIKHEF. The short chambers have two staggered layers of 16 straw tubes, each with 5.5 mm distance between wire planes. The straw inner diameter is 5 mm, the wire diameter is 25 μm. The straws are made of double Kapton XC. These four chambers were mounted close to each other, forming a tracking station with total length along the beam direction of $\sim$14 cm. The wires were oriented vertically, so these chambers measured the horizontal coordinate. The chambers are labelled 6030, 6031, 6033 and 6034 and were installed in this order along the beam

[1]The unrecoverable data losses in TDC however still occured at higher data rates, when many TDC modules were switched on. This noticeably biased the determination of long chambers' efficiency, see below.

direction. The layers of each chamber are labelled A and B, and in the setup the layer A was ahead (upstream) of the layer B.

- Two long (2 m) straw chamber prototypes, made at NIKHEF. These prototypes have two staggered layers of 32 straw tubes each, with 9 mm between layers. The layer geometry is similar to that of the short chambers, with 6 mm pitch, 5 mm straw inner diameter and 25 μm wire diameter. Two types of straws were used in these chambers, double Kapton XC and Kapton-XC + Al windings[2]. The chambers are labelled 2004 and 0604, layers – A and B. The main difference between the two long chambers is that the chamber 0604 has an aluminium foil between the straw layers, connected to the amplifier ground. These two long chambers were installed close to each other and to the station of short chambers, downstream in the beam direction. The wires of these chambers were also oriented vertically. Each channel of these chambers have two wire locators of "twister" type, placed inside the tubes at 66 cm from each end.

- Another 2m long straw prototype, made in Krakow. It is similar to the NIKHEF ones, except for the pitch of 5.2 mm instead of 6 mm.

- The 2m long prototype of the Carbon-coated drift chamber [2]. It has one layer of drift cells, with 5 mm inner diameter, 6 mm pitch and 25 μm wire.

Regarding the long chambers, this note describes only the studies of the NIKHEF prototypes. The results of tests of Krakow and Carbon-coated chambers will be presented in separate notes.

For the measurement of the vertical coordinate, we used two honeycomb chambers, labelled 9001 and 9002. These chambers have two staggered layers each, with 32 channels and 9 mm pitch. They were used as an auxilliary device in the studies of the straw prototypes, and their performance will not be discussed in this note. The measurement of the vertical coordinate was necesssary, because the straw chambers might have been installed slightly non-parallel, and we had to determine their relative stereo angles,

[2]Unfortunately it was possible to study these chambers only in the section with double Kapton XC straws.

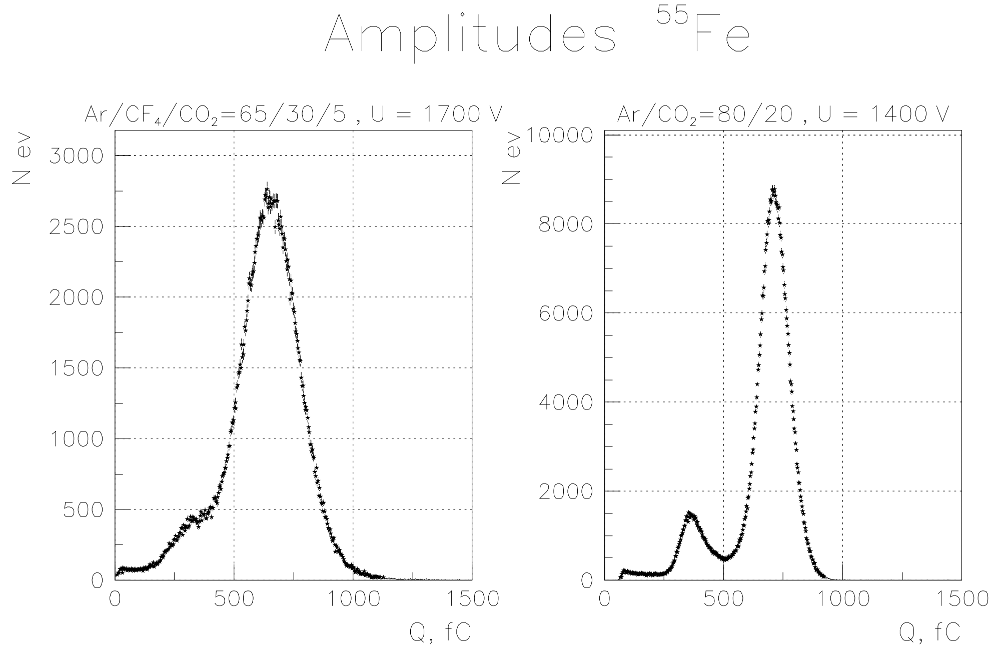


Figure 1: Amplitude spectra for ^{55}Fe for the mixtures $Ar/CF_4/CO_2$=65/30/5 and Ar/CO_2=80/20.

in order to take them into account for example for the measurement of the coordinate resolution.

Below, the chambers will be referred to using their labels; in case one particular layer is mentioned, we append the layer label to the chamber label: for example, 2004B is the layer B of the chamber 2004.

3 Analysis

Our experimental setup was not equipped with an external high precision tracker (e.g. silicon strip detector), therefore for the studies of the drift cell properties, like time-to-distance relations, resolutions etc, we had to calculate the parameters using the chamber data themselves.

The idea of such autocalibration procedures is simple. The particle tracks are known to be straight (or, in case of a nonzero uniform magnetic field, they are circular with known radius). In this assumption, we can find and fit tracks in some set of events. Then, varying the drift cell parameters

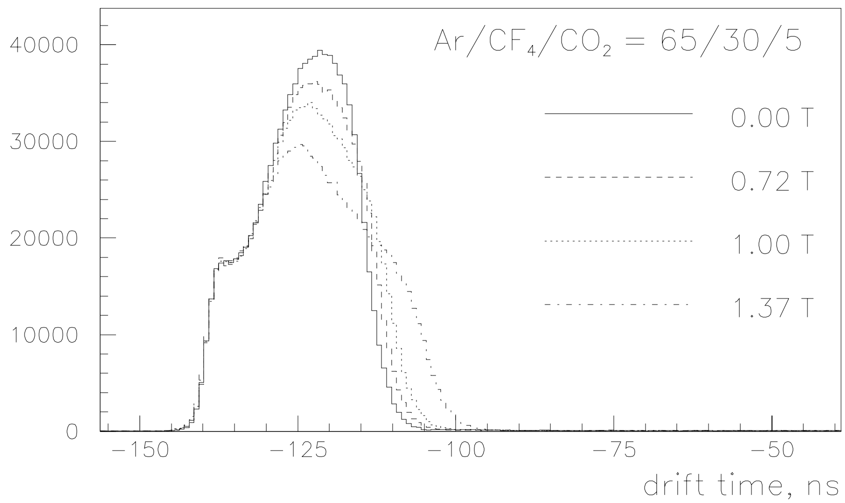


Figure 2: Drift time spectra at different values of the magnetic field

and positions of the chambers, we find the values at which the overall fit quality of the tracks in this data set is the best.

The detailed description of the analysis procedure is beyond the scope of this note. The analysis methods used here are described in [1] and references therein[3].

4 Drift cell properties

The gas mixtures containing CF_4 provide high electron drift velocity, ~ 10 cm/μs. This makes them well suited for applications at LHC.

The LHCb timing requirements for Outer Tracker [4] is that all signals should arrive in 50 ns, which corresponds to two bunch crossing intervals. Taking into account signal propagation time in the straw tube, this limits the maximal drift time to:

- 35 ns for the large tracking stations outside the magnet;

[3]In particular, the basics of the analysis procedure used in present studies are described in a very detailed and comprehensive way in [3].

- 42 ns for the stations inside the magnet (B_{max} ~1.4 T).

The maximal drift time and Lorentz angle depend on the concentration of CF4.

On the other hand, it is well known that there is significant electron attachment in CF_4-based mixtures [5]. This effect is illustrated in Fig.1, where the ^{55}Fe amplitude spectra for gas mixtures Ar/CF_4/CO_2=65/30/5 and Ar/CO_2=80/20 are shown (the high voltages were chosen such that the position of the main 5.9 KeV peak was approximately the same, corresponding to the effective gas gain of about 20000). The difference is clear: in presence of CF_4 the energy resolution is 2 times worse, making the classical Argon escape peak [6] almost invisible. One can expect therefore that for the detection of charged particles the presence of CF_4 will lead to a broader dynamic range of signals. This, in turn, leads to lower efficiency, worse coordinate resolution, and higher crosstalk level because of higher fraction of big signals. So it is important to know how big this effect is. For the final system, it is preferable to keep the CF_4 percentage as low as possible.

Another practical concern is that CF_4 is rather expensive. This is also a good reason to keep the CF_4 percentage as low as possible, within the timing requirements.

It was shown in [7] that the gas mixtures based on Ar, CF_4 and CO_2 can be safely used in chambers with carbon-doped plastic cathodes. In these beam tests we studied therefore the mixtures with different percentages of Ar, CF_4 and CO_2.

4.1 Setup

The studies of drift cell properties were performed using only the set of short (30 cm) chambers. The station of short chambers was placed between the poles of the magnet, in the area of the homogeneous field. The wires were oriented vertically, along the field direction.

We used also one honeycomb chamber, placed in front of the straw station, for the measurement of the vertical coordinate.

The threshold of the preamplifiers of the straw prototype, based on the ASDBLR chip [8, 9], was set to 2.7 fC (1.8 V at the threshold setting

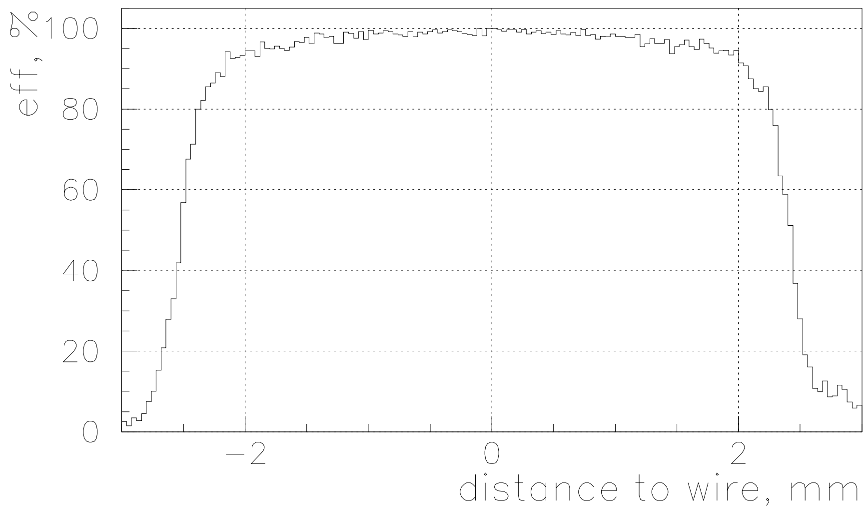


Figure 3: Drift cell efficiency as a function of predicted distance between track and wire, for the gas mixture 65/30/5 at U=1800 V

input). The threshold for the honeycomb chambers was 4.1 fC (2.1 V).

4.2 Measured quantities

The parameters we measured were:

- efficiency, coordinate resolution and crosstalk level as a function of high voltage, without magnetic field;
- total drift time as a function of magnetic field, at high voltage values on the efficiency plateau.

For the measurements of the performance parameters of the chambers, always the same layer was used, 6033A. This layer is the fifth out of eight layers of the station, counting along the beam direction, see Section 2. We have chosen it because of its position in the middle of the straw layers set: the value of the correction factor for the resolution determination (residual scaling factor; see for details [3]) was ∼1.1, which ensured us that the

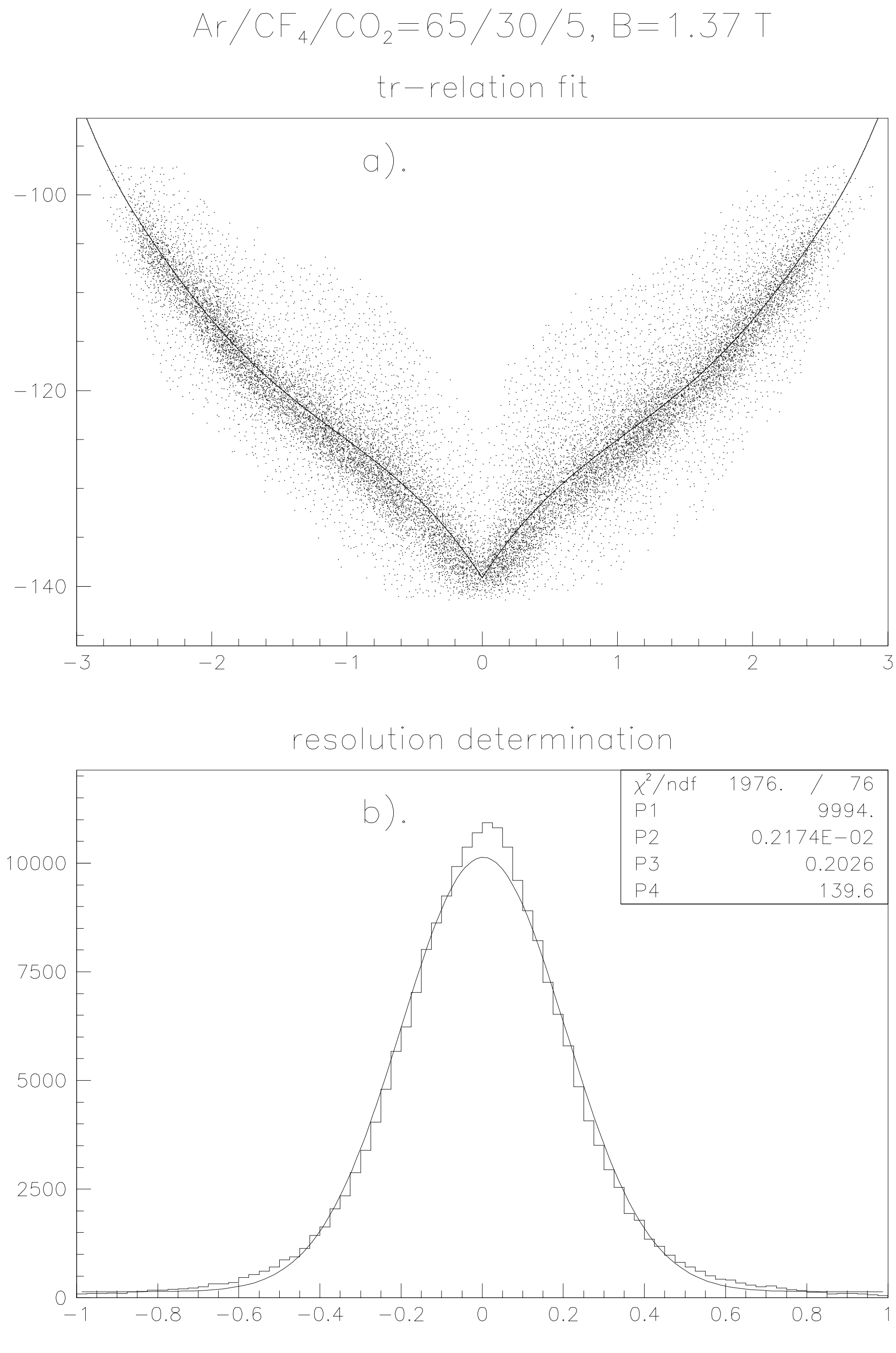


Figure 4: Fit of t(r) relation and resolution determination

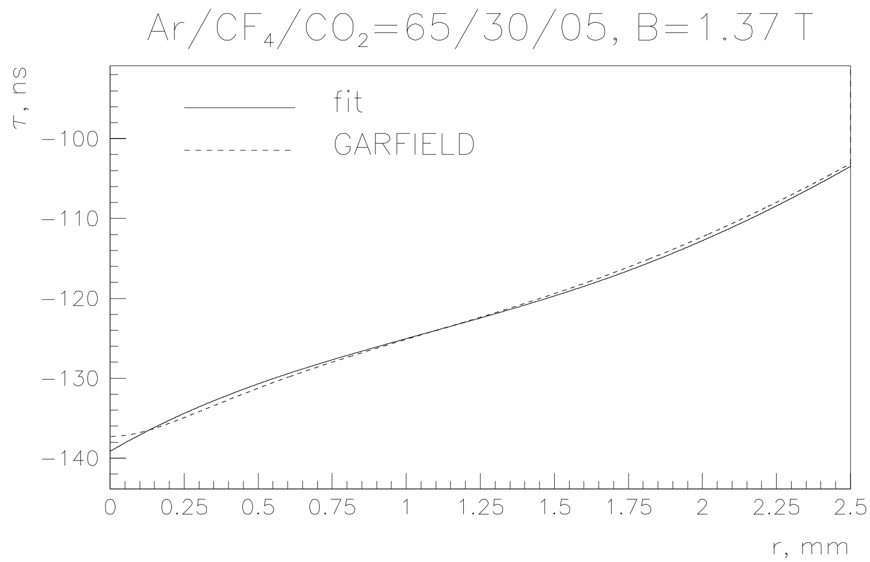


Figure 5: Comparison of the fitted t(r)-relation with the GARFIELD prediction for the gas mixture 65/30/5 in the magnetic field of 1.37 T.

systematic error for the resolution did not exceed several percents of its value.

As an example, the drift time spectra for the mixture 65/30/5 and several values of the magnetic field are shown in Fig.2. The effect of the magnetic field is clearly seen.

The total drift time was determined as an interval containing 98% of signals, with 1% of signals arriving before the beginning and 1% after the end of the interval.

For the measurement of the efficiency, we used the algorithm described in [1]. In order to avoid possible biases, tracks were reconstructed using all layers except the layer under study, in our case 6033A. Then the coordinate of the crossing point of the reconstructed track and the layer 6033A was calculated for each event. If a hit in the layer was found in a certain window around this coordinate (we took it equal to ± 6 mm), the layer was considered to be hit, otherwise not. The drift cell efficiency as a function of the distance between track and wire, averaged over all straws of the layer

6033A, is shown in Fig.3 (the sign of the distance corresponds to the side at which the track approaches the wire).

The average straw efficiency was calculated as $\epsilon = N_{hit}/N_{events} * q_{geom}$, where q_{geom} is a geometrical factor. In our case, for 5 mm tubes with 6 mm pitch, this factor is 6/5.

The coordinate resolution was measured in the following way. After proper position calibration and t(r)-relations fit, the distribution of scaled residuals [3] for all straws in the selected layer was fitted with gaussian+constant, and the standard deviation of the gaussian was taken as the value of the resolution. An example for the gas mixture of $Ar/CF_4/CO_2$=65/30/5 and magnetic field of 1.37 T is shown in Fig.4. Fig.4a shows the scatter plot of measured drift time of a hit associated with a track versus the predicted distance between the track and the wire, for all wires of the layer 6033A; the superimposed curve is the fitted t(r)-relation. Fig.4b shows the corresponding distribution of scaled track residuals; superimposed is the fit with gaussian+constant.

The fitted t(r)-relations are in a good agreement with predictions of the GARFIELD program (version 7.01) [10]. As an example, in Fig.5 one can see the comparison of the fitted curve from Fig.4a and correspondent GARFIELD prediction.

The crosstalk signal is a parasitic signal induced from the hit channel to its neighbours. There are many possible sources of crosstalk in straw chambers, such as electromagnetic pickup from wire to wire in case of resistive cathode, coupling between channels through common ground lines, electromagnetic pickup at printed circuit boards etc. At high amplitude of the true signal, the parasitic signal reaches the discriminator threshold and produces a fake hit in the event. The crosstalk level should be minimized, because such fake hits deteriorate the system's pattern recognition capabilities; they also unnecessarily increase the event size and cause extra deadtime.

Of course, the cross talk level in small chambers may differ very much from that in the final system. In our studies, the crosstalk level was rather an indirect measure of the dynamic range of signals, and used for comparison of gas mixtures. In other words, the higher is the crosstalk level in a small chamber at a given gas mixture, the higher will it be in the final

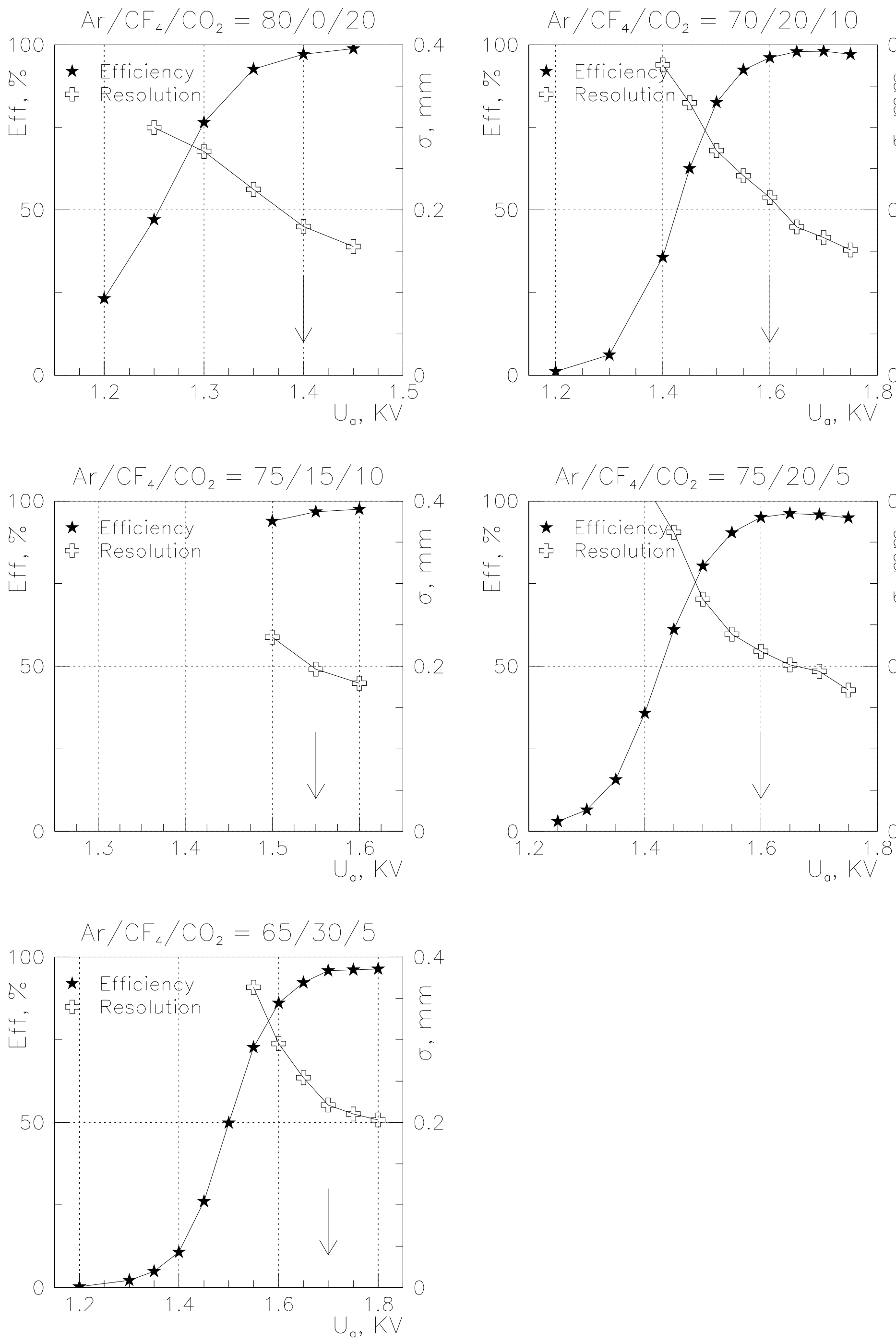


Figure 6: Efficiency and resolution as a function of high voltage for various gas mixtures

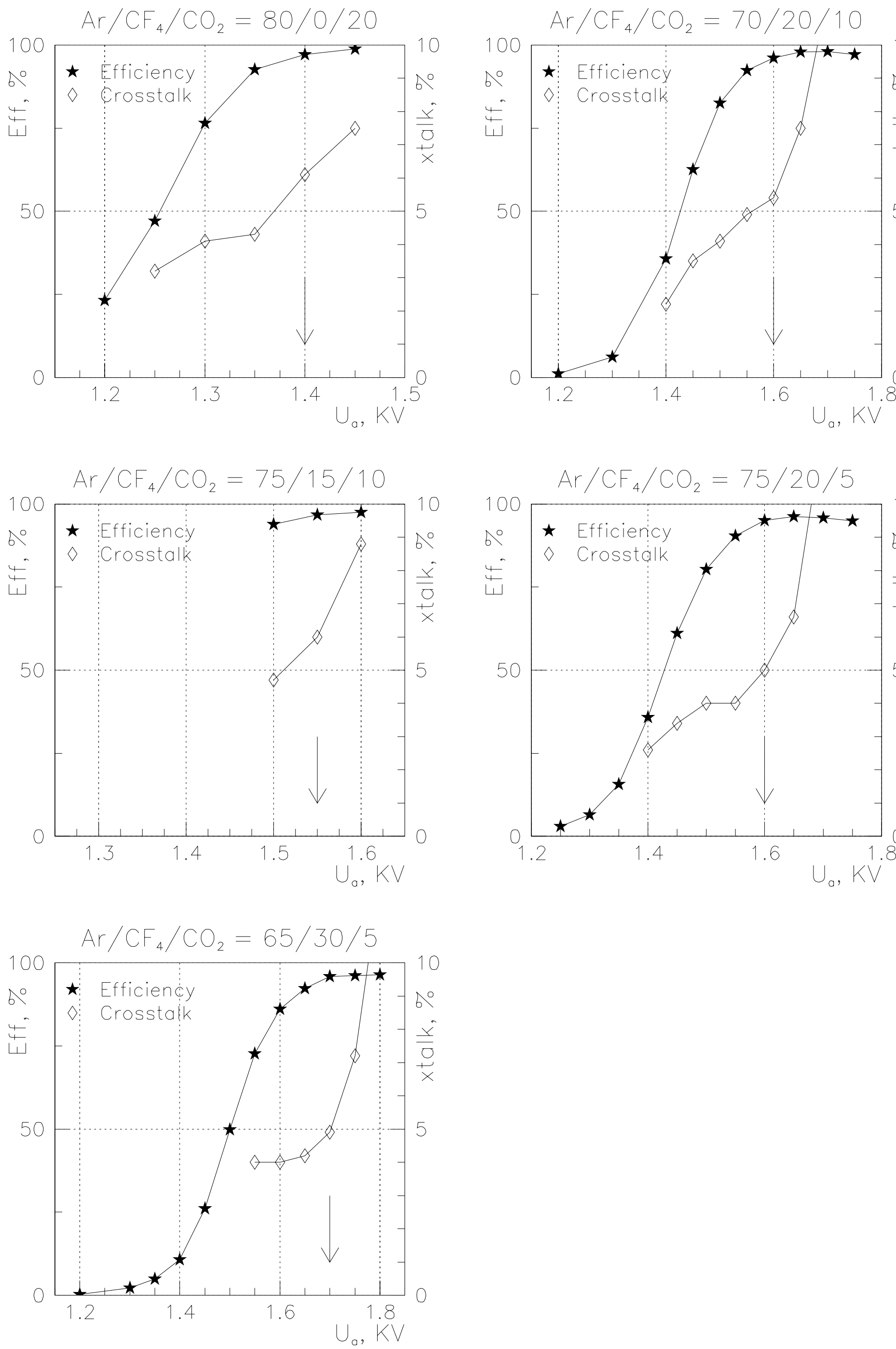


Figure 7: Efficiency and crosstalk level as a function of high voltage for various gas mixtures

system at this mixture.

Our definition of the crosstalk level was the following: for the set of events with one reconstructed track, which had an associated hit in the selected layer, 6033A, we took as the measure of crosstalk level the average number of non-associated hits in this layer per event, assuming that they all arise from crosstalk.

4.3 Results

The total drift times for the seven different gas mixtures at four values of magnetic field are given in Table 1. From this table, one can conclude that the mixture 75/15/10 is the one which has minimal CF_4 content and still meets the LHCb timing requirements (see above).

mixture $Ar/CF_4/CO_2$	τ, ns B = 0 T	τ, ns B = 0.72 T	τ, ns B = 1.0 T	τ, ns B = 1.37 T
80 / 0 / 20	41.2	43.2	44.8	49.1
65 / 5 / 30	39.0	40.5	42.2	45.1
75 / 15 / 10	32.5	34.5	36.3	40.9
75 / 20 / 5	31.4	33.1	35.1	40.8
70 / 20 / 10	31.4	33.0	35.2	39.3
70 / 25 / 5	29.2	30.9	32.8	37.5
65 / 30 / 5	28.2	30.1	32.0	36.0

Table 1: Total drift times for various mixtures and magnetic field values

The coordinate resolution and efficiency as functions of the high voltage are shown in Fig. 6 for five gas mixtures. For the same mixtures, the crosstalk level and again efficiency as functions of the high voltage are shown in Fig. 7. The arrows point to the beginning of the plateau, which was taken as the lowest HV at which the efficiency exceeds 95%.

The essential parameters of these gas mixtures are given in Table 2. One can see that the effect of presence of CF_4 is visible, but not dramatic: the coordinate resolution at the beginning of the plateau is apparently correlated with the percentage of CF_4, it is 0.18 mm for the mixture without CF_4 and 0.22 mm with 30% of CF_4. In the crosstalk level the effect is hardly visible at all: the variations from 4.9% to 6.1% are not correlated with CF_4 content, and can be rather attributed to the precision of determination of

mixture $Ar/CF_4/CO_2$	U, kV	eff, %	σ, μm	τ, ns B=0 T	τ, ns B=1.37 T	cross talk
80 / 0 / 20	1.40	97.2	180	41.2	49.1	6.1%
75 / 15 / 10	1.55	96.7	196	32.5	40.9	6.0%
75 / 20 / 5	1.60	95.0	218	31.4	40.8	5.0%
70 / 20 / 10	1.60	96.2	215	31.4	39.3	5.4%
65 / 30 / 5	1.70	95.9	221	28.2	36.0	4.9%

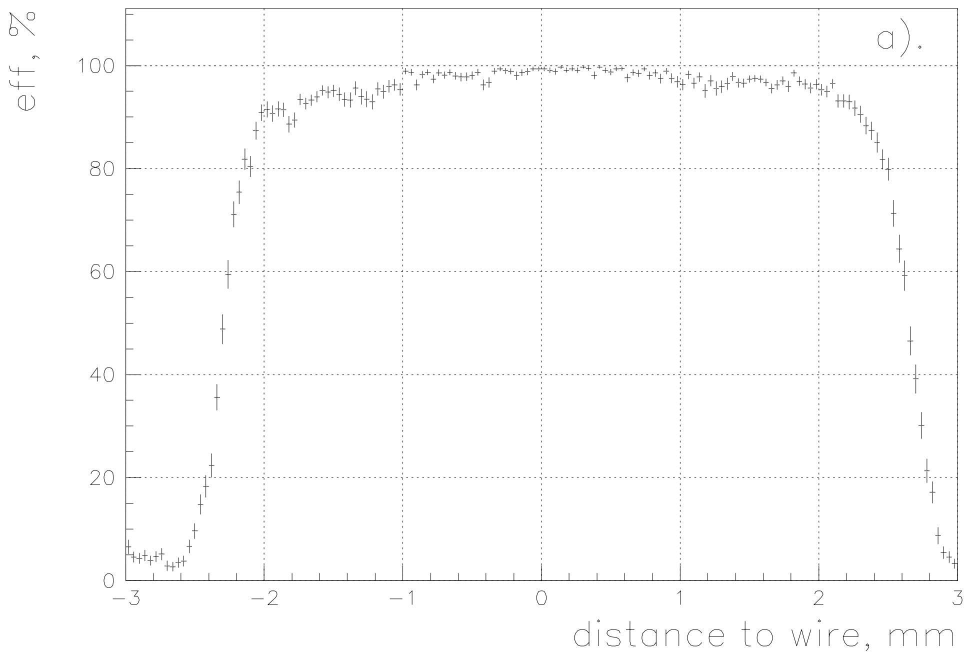
Table 2: Parameters of gas mixtures at the beginning of the plateau

the beginning of the plateau (the high voltage scanning step was 50 V; note the correlation between the crosstalk level and efficiency).

4.4 Measurement of the mechanical precision of chambers

In the beam tests of 2000, the collected statistics allowed us to measure some parameters of the mechanical precision of the chambers' assembly. The method of measurement is explained below. Fig.8 shows the effect of the transversal offset of the wire plane with respect to the straw centres. For this, the layer number 6 (6033B) was chosen. In Fig.8a one can see that the cell efficiency as a function of distance between track and wire is not centered at zero. More details are given in Fig.8b, which shows the distribution of measured drift time versus predicted distance between track and wire. It is clear that the calibration of transversal position of the chamber was correct, because the apex of the "V-shape" points to zero; its "wings" however are asymmetric, which is the consequence of the offset of the wire plane. This offset was determined as the average position of the cell's sensitive area with respect to the wire, that is the averaged distance between track and wire when this wire is hit. The offsets for the eight planes of the short straw chambers are shown in Fig.9.

It was possible also to measure the precision of the positioning of individual wires with respect to their average nominal positions, which were the calibrated average positions of the wire planes. For this we used the average difference between predicted distance from track to wire and measured distance for the hit determined from the measured drift time via the t(r)-relation. The distribution for small chambers is shown in Fig.10 (of course only for the channels with high enough statistics).



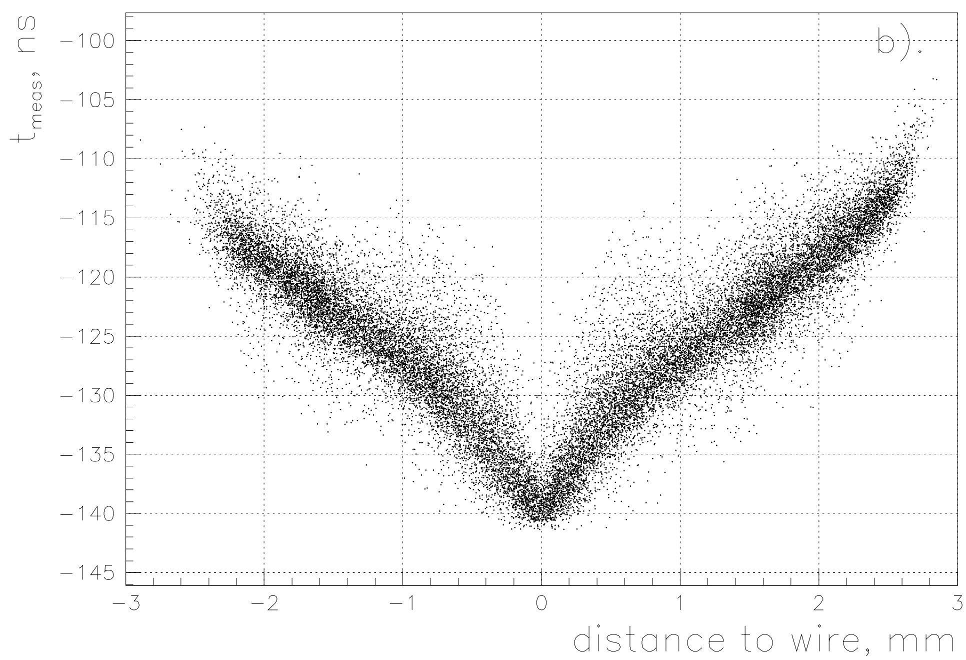


Figure 8: The effect of the offset of the wire planes with respect to the straw centres: a) the efficiency of the cell as a function of the predicted distance between track and wire, b) the distribution of the measured drift times as a function of the distance between track and wire.

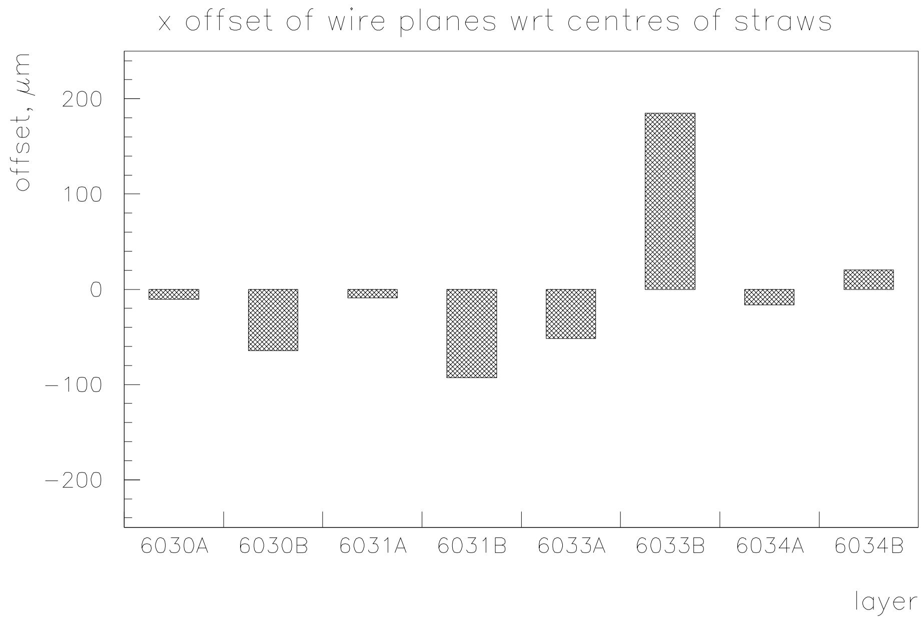


Figure 9: The wire plane offsets for the eight planes of the short straw chambers.

One can see in Fig.9, that in the short chambers the precision of positioning of the wire plane as a whole is $\sim$50-100μm, while within the plane the wires are placed with much better precision, of $\sim 15\mu$m (Fig.10).

5 Long prototype studies

5.1 Setup

For the measurement of the parameters of the long chambers, we used both the short chamber station and long chambers for the track reconstruction, and also the two honeycomb chambers for the measurements of the vertical coordinate. We tested the long chambers in several places along the wire, in order to observe the dependence of the parameters on the distance between the beam spot and preamplifiers.

In these tests we used the gas mixture of $Ar/CF_4/CO_2$=65/30/5 for all the chambers. The short chambers were operated at 1800 V with preamplifier threshold of 2.7 fC (1.8 V). At the long chambers, the high voltage

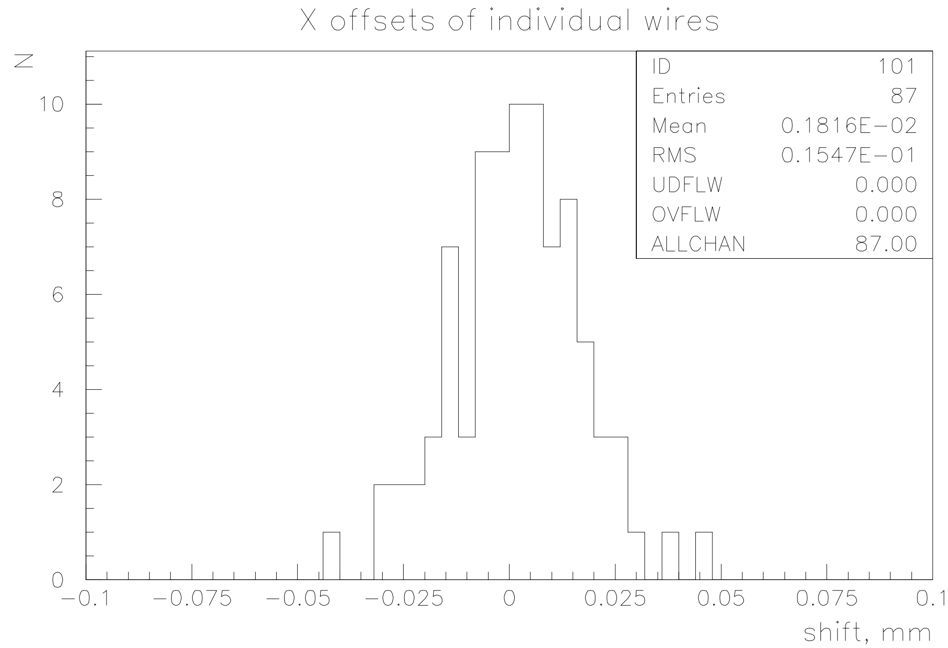


Figure 10: The distribution of deviations of individual wires from their nominal positions for short straw chambers.

was set to 1750 V and the threshold also to 2.7 fC. The threshold on the honeycomb chambers was 4.1 fC (2.1 V), high voltage 1750 V.

5.2 Results

The coordinate resolution of the long prototypes as a function of the position of the beam spot along the chamber is shown in Fig.11. The resolution is somewhat worse than that measured in the same conditions for the short chambers (see Fig.6). There is also some worsening of the resolution towards the far end of the chamber. Qualitatively, such worsening of the resolution is expected, because the signal edge smears when the signal travels to the amplifier. Its magnitude however depends on the particular chamber design.

The apparent efficiency of the long chambers measured in these tests was somewhat too low and varied in the limits 80-90%, without any clear correlation with the position. However the dependence of the efficiency on the distance between the track and the wire (see Fig.12) looks quite similar

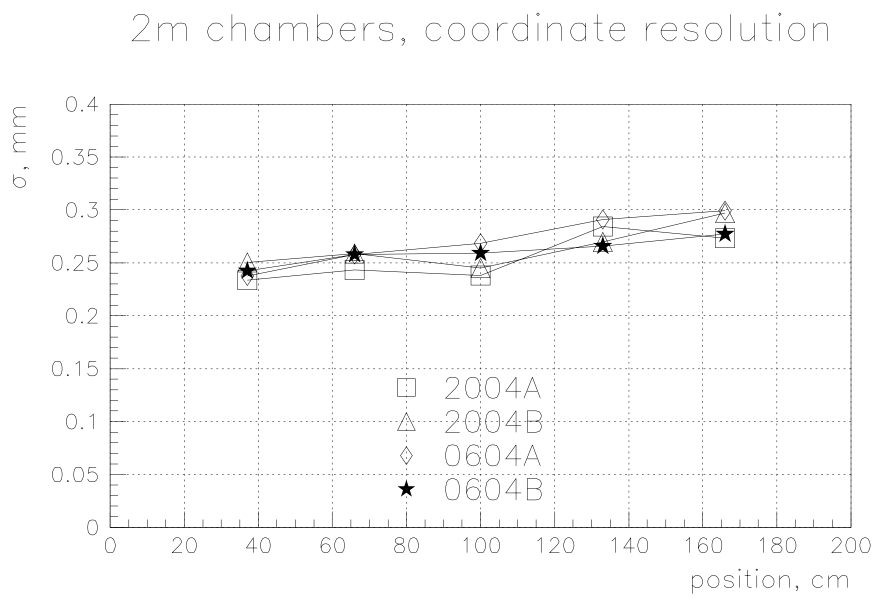


Figure 11: The resolution of the long chambers as a function of the position of the beam spot along the chamber. The end where amplifiers were connected is the one at the position of 0 cm.

to that for the short chambers (Fig.3), having also a flat top. This means that the long chambers were very likely working at the plateau, with actual efficiency $> 95\%$, while the measured efficiency was underestimated.

Closer look to the data showed that in runs with long chambers a very big fraction of the events had the TDC error flag set, indicating that there were (unrecoverable) hit losses. Therefore we concluded that we cannot quote any reliable data on the long chambers efficiency.

It is important to mention, that in the data on the gas mixtures studies described in the previous section, there were no events with error flag set, so the efficiencies obtained in these studies were not biased by electronics problems. Also the resolution measurements for the long chambers are not biased by these data losses, because the method is independent on the efficiency of the chambers.

Fig.13 shows the dependence of the efficiency on the coordinate along the wire in the regions of wire locators. One can see that the 10 mm long wire locators cause an inefficiency zone of $\sim$12 mm (FWHM).

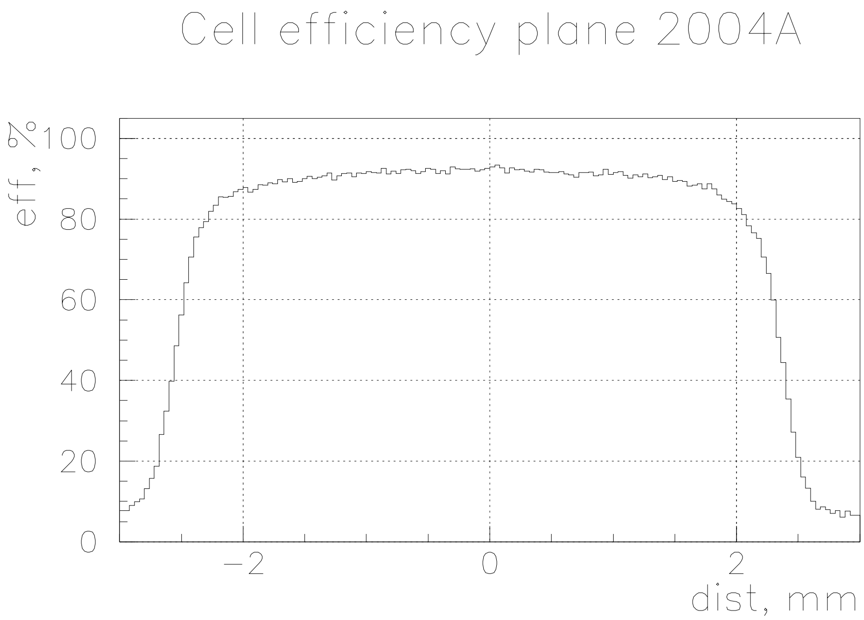


Figure 12: Drift cell efficiency in long chambers (layer 2004A) as a function of predicted distance between track and wire, for the gas mixture 65/30/5 at U=1750 V

Fig.14 shows the dependence of the crosstalk level on the position. One can see that the crosstalk level is very high, especially in the chamber 2004, which does not have ground foil between the two layers. The growth of its crosstalk level towards the far end probably results from the poor grounding. In the chamber 0604 the crosstalk level is much better and less dependent on the distance, but still too high.

It should be noted that these poor results were obtained for straws with double Kapton-XC winding. Recent lab tests have shown meanwhile that straws with an outer winding of aluminium have much lower crosstalk level [11].

The level of crosstalk between the two layers of the same chamber was measured in the following way: the high voltage at one plane was set to zero, while at the other plane remained at the working point. For the level of this kind of crosstalk, we took the "efficiency" of the layer which was switched off. This test showed a 26% crosstalk level between the layers of chamber 2004, while for the chamber 0604, which has ground foil between the layers, it was ∼0.02%.

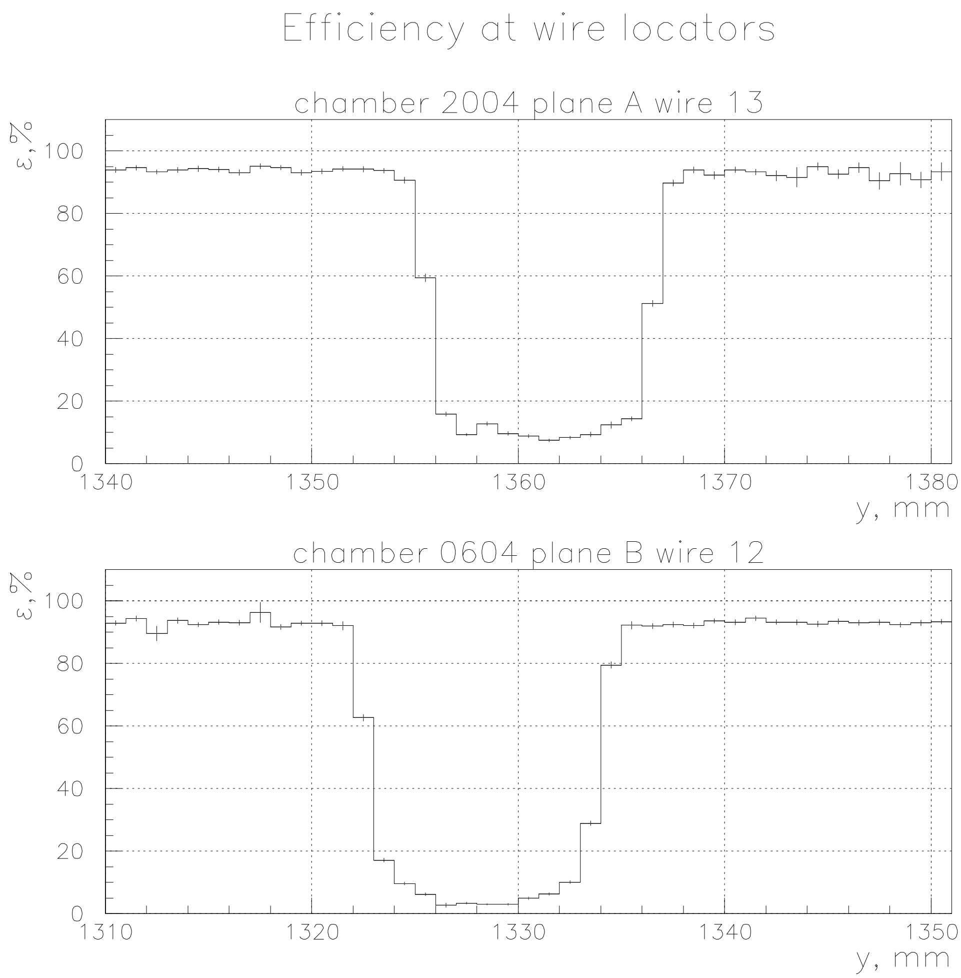


Figure 13: The efficiency in the region of wire locators as a function of the coordinate along the wire.

Fig.15 shows the transversal offsets of wire planes from the centres of the straws for all the four layers, measured in the same points along the chambers using the method described in Section 4.4. The values of the offsets are sizeable, reaching for some planes ∼0.5 mm at the ends. The centering effect of wire locators is visible. Positive is the fact that such big mechanical errors, up to 0.5 mm, did not affect the stability of the chambers' operation.

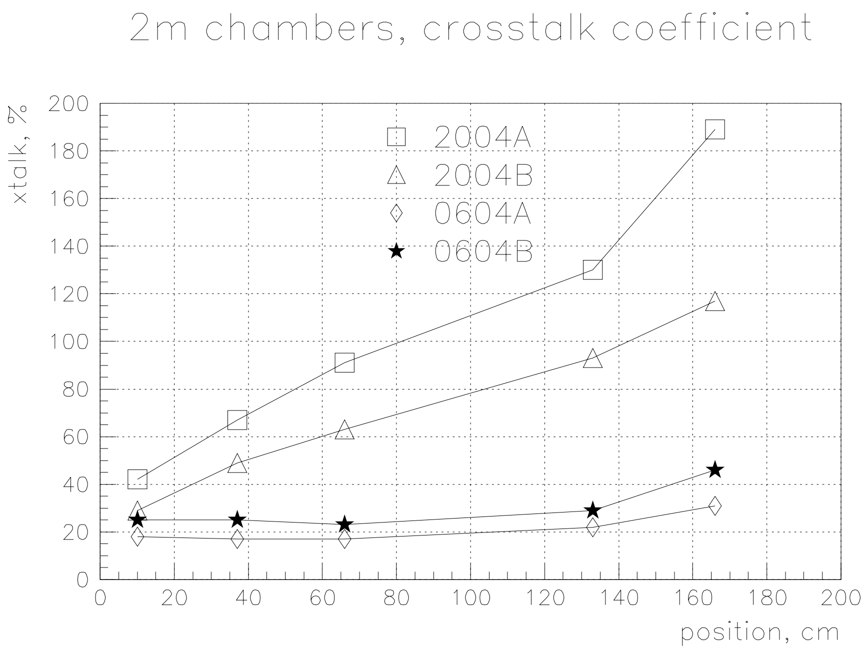


Figure 14: The crosstalk level in the long chambers as a function of the position of the beam spot along the chamber.

6 Conclusions

The drift cell properties were studied using the short prototypes for several $Ar/CF_4/CO_2$ mixtures, with the CF_4 content in the range of 0-30%. These studies showed that in order to match the LHCb timing requirements, the minimum CF_4 content is about 15%. The performance is almost independent on the CF_4 percentage, in spite of the noticeable effect of electron attachment. However the minimization of the CF_4 percentage reduces cost and also slightly improves the resolution.

The performance study of the 2m long prototypes of the LHCb Outer Tracker straw chambers showed that they are fully operational, with coordinate resolution of about 250 μm. The wire locators work properly.

The main problem of these chambers is too high level of crosstalk between channels. Much better cross talk suppression has meanwhile been obtained in lab tests with aluminium shielded straws in a modified chamber

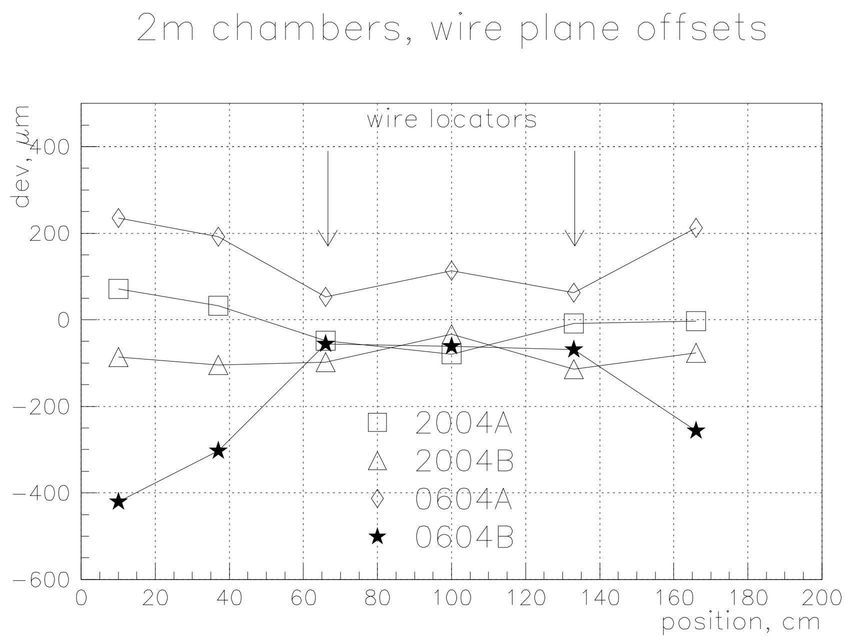


Figure 15: The offset of the wire plane with respect to the straw centres in the long chambers as a function of the position of the beam spot along the chamber.

design [11].

The analysis also showed that the accuracy of the assembly of the long chambers was not very high, the displacement of the wire planes from the straw centres achieves 0.5 mm. This however did not cause any kind of instability of the chambers' operation.

References

[1] Rutger van der Eijk, “LHCb Outer Tracker prototypes”, LHCb internal note 2000-057, 2000

[2] F.Blekman, “Carbon-coated drift chambers: An Ageing experiment”, University of Amsterdam, graduation thesis, 2000

[3] W.Hulsbergen et al, “Calibration of Hera-B Outer Tracker Chambers in a Cosmic Ray Setup at NIKHEF”, HERA-B note 00-014, 2000

[4] LHCb Technical proposal, CERN/LHCC 98-4 LHCC/P4, 20 February 1998.

[5] W.S. Anderson et al, “Electron attachment, effective ionization coefficient, and electron drift velocity for CF_4 gas mixtures”, NIM A323 (1992), 273-279.

[6] F. Sauli, “Principles of operation of multiwire proportional and drift chambers”, CERN 77-09, 1977.

[7] G.W. van Apeldoorn, “Ageing studies of straw tube chambers”, LHCb internal note LHCb-2001-003.

[8] B. Bevensee et al, “A Amplifier Shaper Discriminator with Baseline Restoration for the ATLAS Transition Radiation Tracker”, IEEE Transaction on Nuclear Science, vol. 43, 1996.

[9] V. Gromov, “Study of operational properties of the ASDBLR chip for the LHCb Outer Tracker”, LHCb internal note LHCb 2000-054, 2000.

[10] http://consult.cern.ch/writeup/garfield/

[11] V.Gromov, T.Sluijk, “Electrical properties of various types of straw tubes considered for the LHCb Outer Tracker”, LHCb internal note LHCb-2001-001.