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Asymmetric and double-cathode-pad wire chambers for the LHCb muon system

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Received 6 January 2005; received in revised form 19 July 2005; accepted 8 August 2005

Abstract

We present results from two types of Multi-Wire Proportional Chambers (MWPCs) with wire pitch of 1.5 mm and cathode–cathode distance of 5 mm intended for triggering purposes in the LHCb experiment. Both prototypes use cathode readout because this allows arbitrary segmentation in order to achieve the required granularity. One MWPC prototype uses a symmetric wire–cathode distance (2.5/2.5 mm) with double cathode readout, which doubles the signal compared to reading only one cathode. The second prototype uses an asymmetric wire–cathode distance (1.25/3.75 mm) with single cathode readout which also doubles the signal and in addition reduces the width of the induced charge distribution and therefore reduces the crosstalk for small cathode pads. We also performed a dedicated optimization of readout traces and guard traces in order to reduce the pad–pad crosstalk. Both prototypes show a few hundred volts of operating plateau defined as the region with 99% efficiency in a 20 ns time window. Close to the plateau end, a time resolution of better than 3 ns was achieved.

PACS: 29.40.Cs; 29.40.Gx

Keywords: MWPC; Asymmetric wire chamber; Double cathode pads; Accumulated charge; Cluster size; LHCb

1. Introduction

The muon detector of LHCb (the Large Hadron Collider Beauty experiment at CERN) consists of five trigger stations (one in front of the calorimeter and four behind the calorimeter) which are placed along the beam axis and separated by iron filters [1]. A muon trigger requires the coincidence of hits in all stations within the LHC bunch crossing time of 25 ns in a certain spatial window that selects the transverse muon momentum. Therefore we require each muon station to have a time resolution better than 4 ns and efficiency >99%. Multi-wire proportional chambers (MWPCs) with wire readout or cathode pad readout (in places where smaller segmentation is needed) are used for this purpose. The MWPCs use a 5 mm cathode separation, 1.5 mm wire pitch and 30 μm wires positioned symmetrically between the cathodes. The used gas mixture is $Ar/CO_2/CF_4$ 40/40/20. Due to the small wire pitch of 1.5 mm, the time resolution of the detector does not depend on the position of the particle track with respect to the wires but it is dominated by the signal-to-noise ratio of the detector signals. Gas gain and electronics noise are therefore the key parameters determining the time resolution [2]. Each muon station behind the calorimeter will consist of four 'standard' detector layers (Fig. 1a). Only one cathode is segmented while the other one is grounded. At the typical operating voltage of 2.95 kV we find a gas gain of 2.5×10^4. The muon station in front of the calorimeter will use only two detector layers in order to minimize the radiation length, which requires a gas gain of 5×10^4 at the operating point. The detectors in this station that are close to the beam pipe experience the highest particle rates (0.5 MHz/cm^2) and require the smallest granularity ($2 \times 1\,cm^2$). Therefore a lower gas gain to decrease aging effects and a narrower cathode charge distribution to reduce crosstalk are desired. We investigated an asymmetric chamber with single cathode readout

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doi:10.1016/j.nima.2005.08.097

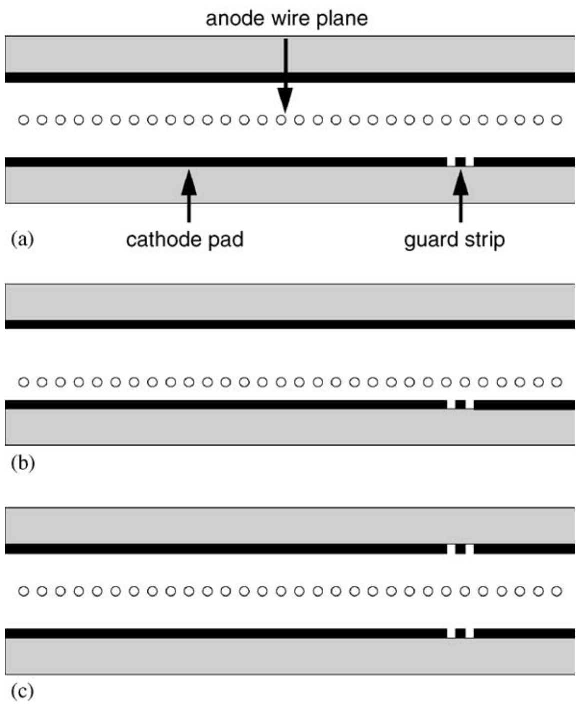

Fig. 1. Geometry of (a) the 'standard' symmetric MWPC, (b) an asymmetric MWPC and (c) a double cathode MWPC.

(Fig. 1b) and a symmetric chamber with double cathode readout (Fig. 1c) to reduce the gas gain with respect to the 'standard' chambers (Fig. 1a) while keeping the same signal-to-noise ratio. The asymmetric chamber shows a narrower cathode charge distribution in addition.

The specific requirements for the detector close to the beam pipe are

- a rate capability up to 0.5 MHz/cm^2;
- a horizontal cluster size (average number of firing channels per track in the bending plane for an uniformly irradiated chamber) of less than 1.2;
- an accumulated charge not exceeding 1 C/cm of wire in 10 years of LHCb operation to limit aging problems [3].

The 'standard' LHCb MWPC design (Fig. 1a) would stand the rate requirement but lead to an accumulated charge of 1.2 C/cm in 10 years of LHCb operation. The two alternative designs described in this report can be operated at lower gas gain which would lead to an accumulated charge of <1 C/cm during the lifetime of the experiment. The expected cluster size for the standard LHCb MWPC design is around 1.5 which can be reduced with the asymmetric design.

2. Chamber parameters and signal characteristics

Asymmetric wire chambers have been considered since the development of wire chambers [4]. Several detectors have been described incorporating a plane of wires and a gap with thickness of only a few hundred micrometres between the wire and the lower cathode plane [5–8]. The aim of those developments was to optimize the MWPC for resolving the track coordinates of particles with a spacial resolution of about 100 μm in a very high rate background (up to a few MHz/cm^2). We investigate an asymmetric chamber in order to allow operation at lower gas gain and in order to reduce the cluster size (i.e. width of the cathode charge distribution).

The total induced charge on an electrode in any detector is equal to the total charge that has arrived at this electrode, once *all* charges have stopped moving. In a symmetric wire chamber the total charge induced on each cathode is therefore on average half of the charge induced on the wires. Decreasing the distance between cathode and wire, the total induced charge will decrease accordingly since there is less primary ionization in the smaller gas gap. In case we read out the cathode and wire signals with electronics of only 10 ns integration time, the picture is entirely different. After a time of 10 ns, the avalanche ions have moved only a few wire diameters away from the wires, so in order to determine the pulseheight of the amplifier output we have to investigate the *weighting fields* close to the wire surface. The weighting field of an electrode is defined as the electric field in the detector if the electrode in question is put to unit potential and all other electrodes are grounded. These weighting fields together with the movement of the charges determine the signal shape through Ramo's theorem [10] and for the MWPC geometries discussed in this report they are calculated either with analytic formulas or GARFIELD [9].

In the following we assume an amplifier with 10 ns integration time and a constant gas gain. In case we reduce the cathode to wire distance symmetrically from 2.5 to 1.25 mm, the pulseheight on the cathodes *increases* by a factor 1.5. Since for practical reasons the distance between the cathodes had to be kept at 5 mm, an asymmetric geometry of 1.25 mm and 3.75 mm cathode to wire distance was chosen, which reduces the pulseheight by a factor 0.4 on the 'far' cathode and increases the pulseheight by a factor 1.8 on the 'near' cathode.

Fig. 2a shows the cathode charge distribution induced by an avalanche on a wire at position 0 for the symmetric and asymmetric chamber. In the symmetric case the charge distribution has the same shape for both cathodes. The asymmetric (3.75/1.25 mm) MWPC shows a 'peaked' charge distribution on the cathode close to the wires and 'wide' charge distribution on the opposite cathode.

Fig. 2b shows the pulseheight (amplifier with 10 ns integration time) for a pad with an edge at a given distance from the particle track position. The pulseheight is normalized to the pulseheight in the symmetric chamber. The pulseheight on a single cathode is a factor 1.8 larger for the asymmetric chamber. Therefore we can reduce the gas gain by a factor 1.8 in order to arrive at the same signal height. In addition, the cathode charge distribution is narrower which will reduce the crosstalk.

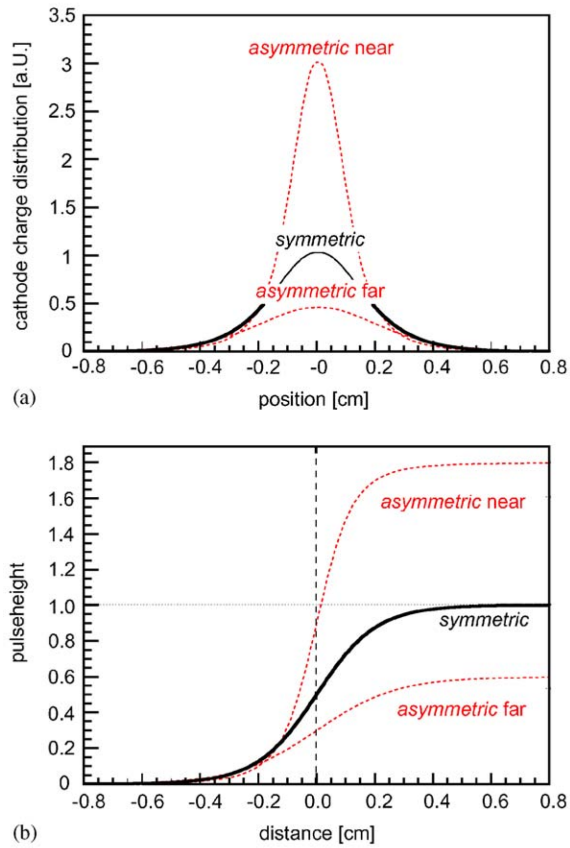

Fig. 2. (a) Cathode charge distribution for the symmetric and asymmetric MWPC. (b) Pulseheight on a single cathode as a function of distance of the cathode pad edge from the particle track position. The pulseheight is a factor 1.8 larger for the asymmetric MWPC. The curves were obtained using GARFIELD [9].

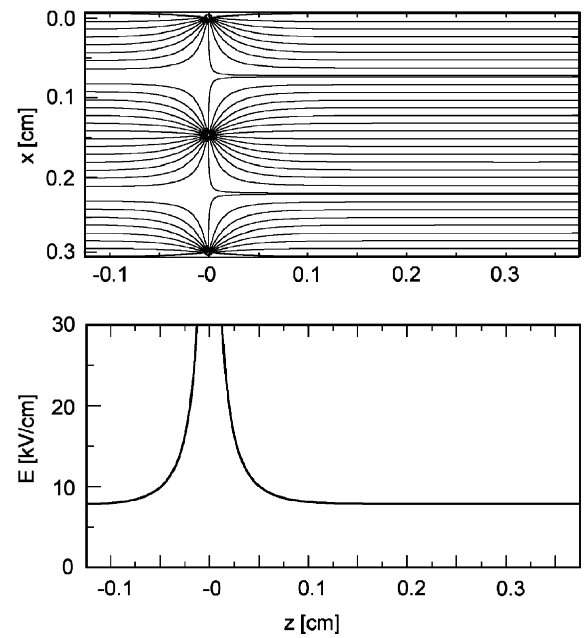

Fig. 3. Electron drift lines in the asymmetric MWPC (top) and electric field across the chamber towards a wire (bottom) simulated with GARFIELD.

Using cathodes on ground potential for the asymmetric chamber would result in a very asymmetric field and a very large surface field ($>10\,\mathrm{kV/cm}$) on the readout pad surface. Therefore the 'far' cathode is set to negative voltage, the wires are on positive voltage and the readout pads are on ground potential. The ratio of voltages is chosen such that the electric field is symmetric which gives exactly a factor of -1 for the specific 1.25/3.75 mm geometry. This factor of -1 is true only for this specific geometry of 1.25/3.75 mm and can take on any value for other geometries. As shown later, a typical operating voltage is $-2\,\mathrm{kV}$ ($+2\,\mathrm{kV}$) on the cathode (wire). Fig. 3 shows the chosen dimensions of the drift cell, some drift lines and the value of the electric field across the gap.

Fig. 4a and b shows simulated cluster sizes for an asymmetric chamber and a symmetric double cathode chamber for random perpendicular tracks. We find 99.5% efficiency at a threshold set to 17% (22%) of the average pulseheight. We see that the asymmetric chamber requires a signal-to-noise ratio that is a factor 1.3 higher than the symmetric chamber in order to arrive at the same efficiency. The asymmetry provides a factor 1.8 in pulse height and the signal-to-noise ratio has to be 1.3 times larger, so we expect that for the asymmetric chamber the gas gain can be lowered only by a factor 1.4 with respect to the 'standard' chamber in Fig. 1a. For the symmetric double cathode readout we do, however, expect to be able to lower the gas gain by a factor 2. At the operating point we expect an average cluster size of 1.17 (1.25) for the asymmetric (symmetric) chamber.

A schematic image of the readout and current flow for the two chambers is shown in Fig. 5.

3. Design of the prototype chamber

The two chamber designs were incorporated in a single module. The active area of the detectors is $24 \times 20\,\mathrm{cm}^2$ and the readout pad dimensions are $1 \times 2.5\,\mathrm{cm}^2$ leading to 192 readout pads per layer (Fig. 6). The four gaps of the prototype chamber are electrically connected in pairs before the readout chip, giving two independent double gaps. The two double gaps are built using the two different designs: one double gap with the asymmetric gap design and one double gap with double cathode pad readout. The panels are built of a honeycomb structure sandwiched between printed circuit boards (PCBs). Fig. 7 shows a cross-section of the chamber. The chamber is sealed using an O-ring and the gap size is ensured using ten 5 mm spacers per gap.

4. Readout traces and crosstalk

The cathode structure is formed on a 1.6 mm printed circuit (PC) board glued on a 5 mm honeycomb structure. Ideally the readout electronics would be positioned right

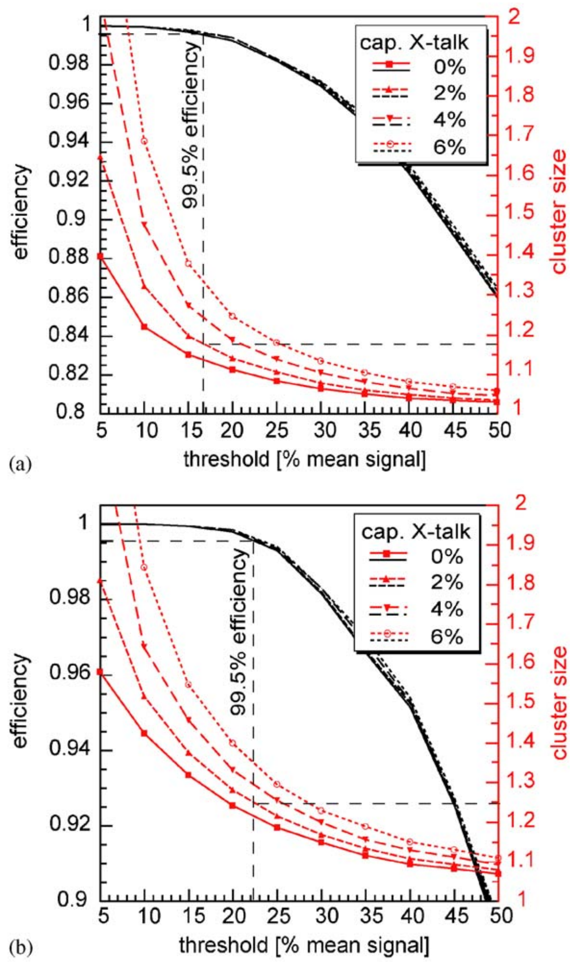

Fig. 4. Efficiencies and cluster sizes at different thresholds (% of the truncated mean of the signals) simulated with GARFIELD. We use double gaps, the $Ar/CO_2/CF_4$ 40/40/20 gas mixture, three 1 cm pads, and random perpendicular tracks. (a) asymmetric, (b) double cathode pad readout. The capacitive crosstalk from 0% to 6% is included by adding this amount of the signals to its two neighbour pads.

behind the cathode pads. However, space considerations require a solution where the signals are brought to the side of the chamber. This is done by using traces on the 'down side' of the PC board as shown in Fig. 8.

In order to minimize crosstalk from these signal lines to other pads one would ideally use a multilayer board with an intermediate ground plane that decouples the traces from the pads. This would, however, result in a very large pad-ground capacitance, causing excessive noise on the frontend electronics. Therefore a scheme with grounded guard traces of 0.25 mm width between the readout traces of 0.25 mm width was adopted. These guard traces reduce the coupling of the signal traces to the pads. The direct pad–pad coupling is reduced in addition by using a grounded guard trace of 0.5 mm between the readout pads. For the specific pad geometry we have cathode pad capacitances C_d between 20 and 30 pF. The mutual pad capacitance C_{pp} is around 1 pF.

The signal propagation time along the wires and the traces is very short compared to the used amplifier peaking

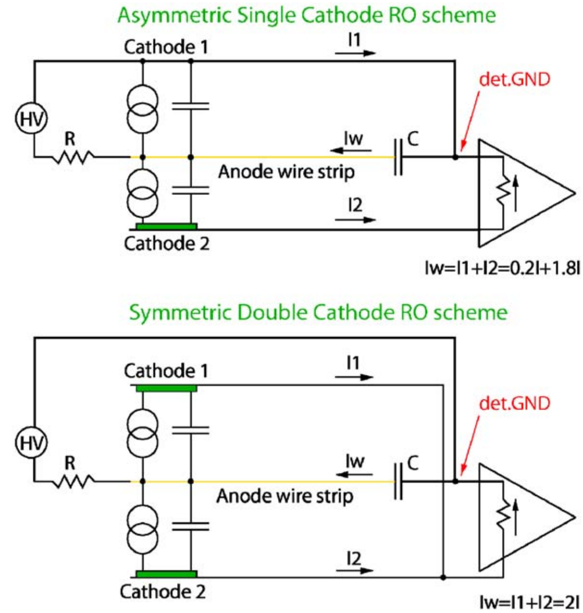

Fig. 5. The current flow in the two detector types.

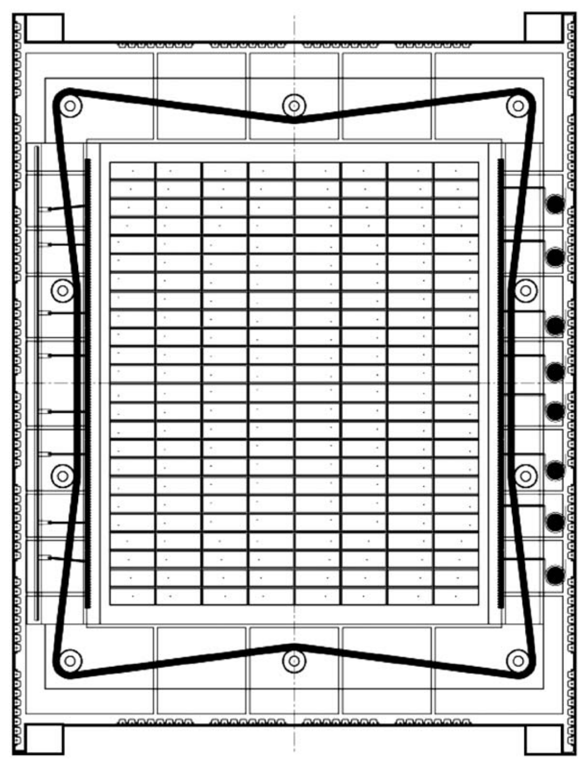

Fig. 6. Layout of the cathode planes of the tested prototype. The wire fixation bars are to the left and right. The O-ring and the 10 round spacers are visible.

time of ≈ 10 ns. Therefore the crosstalk is determined by the capacitance C_{pp} between the electrodes. The electrical model of two neighbour pads is shown in Fig. 9 with a transfer function of

$$\frac{i_2}{i_1} = \frac{C_{pp}}{C_d} \frac{i\omega R_{\rm in} C_d}{1 + i\omega R_{\rm in} C_d} \quad \text{for } C_{pp} \ll C_d. \tag{1}$$

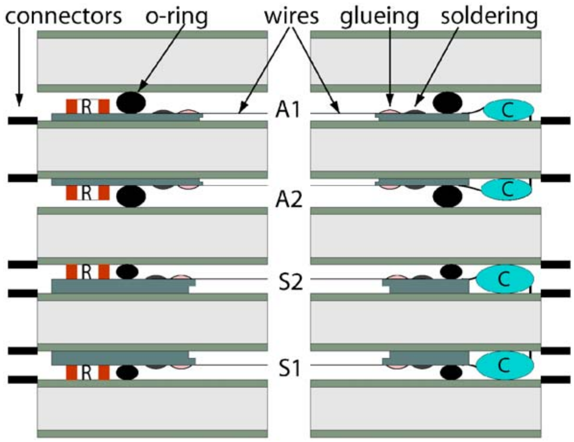

Fig. 7. Cross-sections of the chamber. Left: The wire fixation bar where the loading resistors (100 kΩ) are situated. Right: The opposite wire fixation bar with the capacitors that connect the wires to ground (680 pF). The wires are glued and soldered to the wire fixation bars. The O-rings with two different diameters are shown.

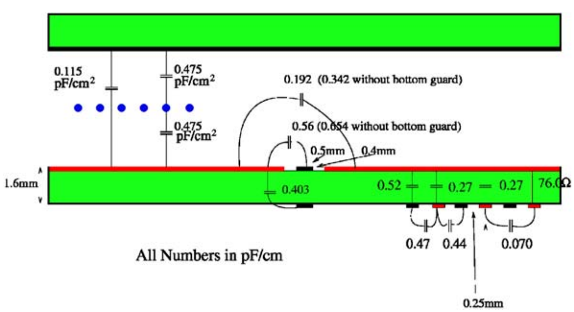

Fig. 8. Dimensions and capacitance values for the optimized readout traces. Unless indicated differently, all numbers are in pF/cm.

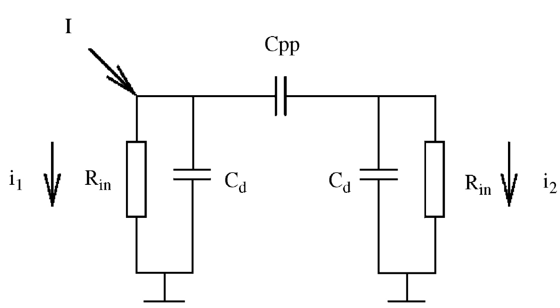

Fig. 9. Circuit diagram of two neighbouring cathode pads.

We see that the crosstalk will be strictly proportional to the mutual pad capacitance C_{pp}. For very high bandwidth amplifiers ($\omega \to \infty$) and/or very large amplifier input resistance R_{in} the crosstalk approaches the value C_{pp}/C_d which would reach 5% in our case. For the parameters $R_{\text{in}} = 25\,\Omega$ and bandwidth of 20 MHz the capacitive crosstalk is, however, $<1\%$, so it is negligible.

5. Test beam results

The chamber was tested in the T11 test beam facility at CERN. Two FE-boards with the ASDQ chip [11] have been mounted on the chamber. All tests have been done with the $Ar/CO_2/CF_4$ (40/40/20) gas mixture. We used two large trigger scintillators and a hodoscope with eight horizontal and vertical strips each. To be able to scan the small pad sizes of the chamber we also used a small finger scintillator (3 mm wide) in the trigger system. The beam consisted mainly of 3.6 GeV pions. The particle rate on the scintillators was between 150 and 180 kHz.

5.1. Efficiency and time resolution

Measured efficiencies, the time r.m.s. and the shift of the average threshold crossing time with the high voltage (‘time walk’) at a threshold of 240 mV (corresponding to about 6 fC) are shown in Fig. 10. The working point ($>99\%$ efficiency in 20 ns time window) is ± 2 kV (2.95 kV) for the asymmetric (symmetric) chamber. These voltages corre-

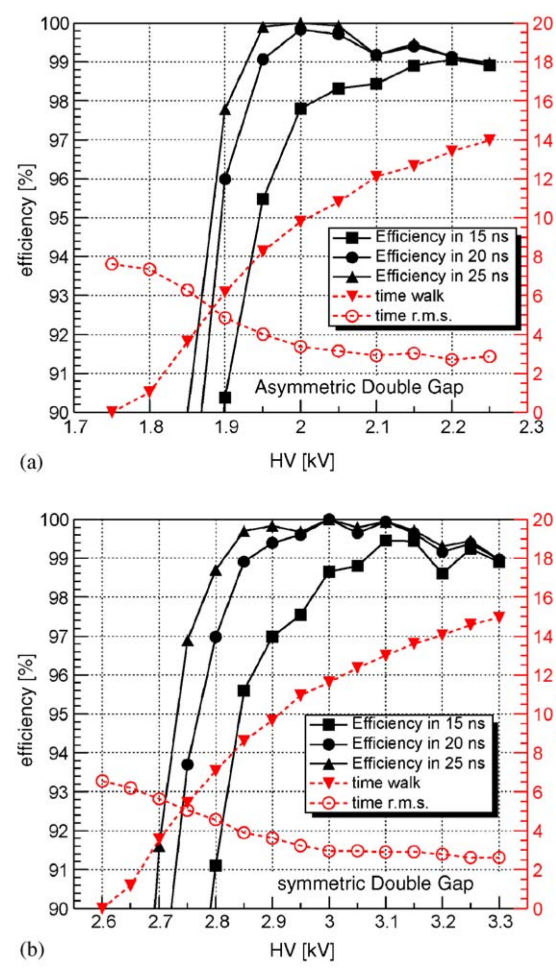

Fig. 10. Single pad efficiencies in 15, 20, 25 ns time windows and timing for double gaps. The lowest efficiency curve is for 15 ns. (a) Asymmetric, (b) double cathode pad readout.

spond to a gas gain of 3.3 (2.5) $\times 10^4$, so as expected we can lower the gas gain only by a factor ≈ 1.5 for the asymmetric chamber. At the working point the time r.m.s. is about 3.75 ns, reaching less than 3 ns at higher voltages. Both double gaps do not show any sparks or trips up to voltages of 2.3 kV (3.35 kV). The slight decrease of efficiency with high voltage is due to increased pulse width and therefore signal pileup.

5.2. Cluster sizes

We assume that the beam of particles is evenly distributed on the small pads. We investigated the cluster size in two different ways:

Horizontal cluster size: The crucial number for the detector performance in the LHCb muon trigger is the cluster size in the bending plane of the detector. We irradiated two pads as is shown in Fig. 11a. The cluster size is calculated as the number of pads that have a hit out of the two irradiated pads and the two neighbours divided by the number of events that are efficient on those four pads. This number we can compare with the simulation results in Section 2.

Full cluster size: We irradiate a larger area as shown in Fig. 11b. The cluster size is calculated as the number of pads that have a hit out of all 16 pads divided by the number of events that are efficient on all pads.

All cluster sizes are within a 50 ns time window.

The results for the 'horizontal' and 'full' cluster size at different high voltages and a threshold of 300 mV ($\approx$ 7 fC) are shown in Fig. 12. At the working point of 2 kV (2.95 kV) the horizontal cluster size is 1.2 (1.4) for the asymmetric (double cathode pad) chamber. These measurements are a bit larger than expected from simulation. It was verified that capacitive crosstalk is $<2\%$, so it cannot explain the discrepancy. The most probable explanation is divergence of the particle beam.

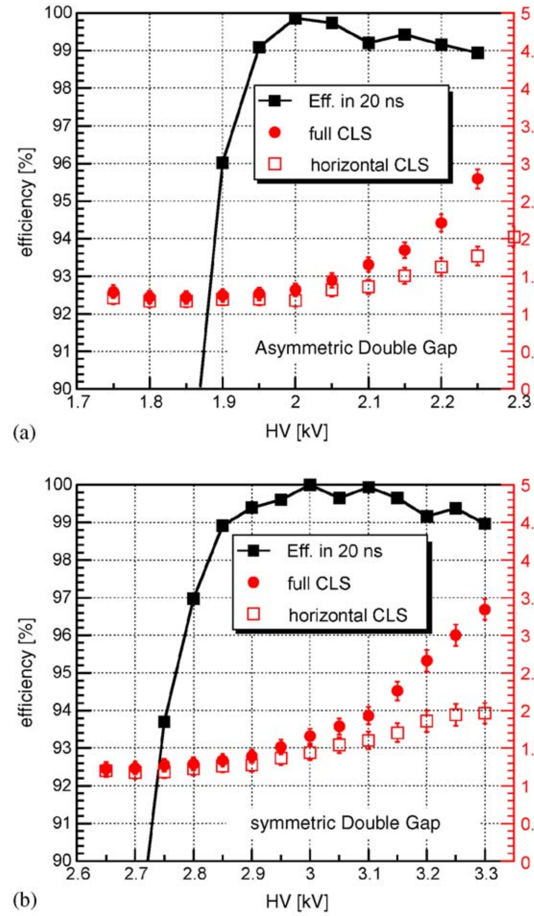

Fig. 12. The double gap cluster size results for the two different selections together with an efficiency curve for 300 mV ($\approx$ 7 fC) threshold. (a) Asymmetric, (b) double cathode pad readout. The triangles show the 'full' cluster size data corrected for one noisy channel.

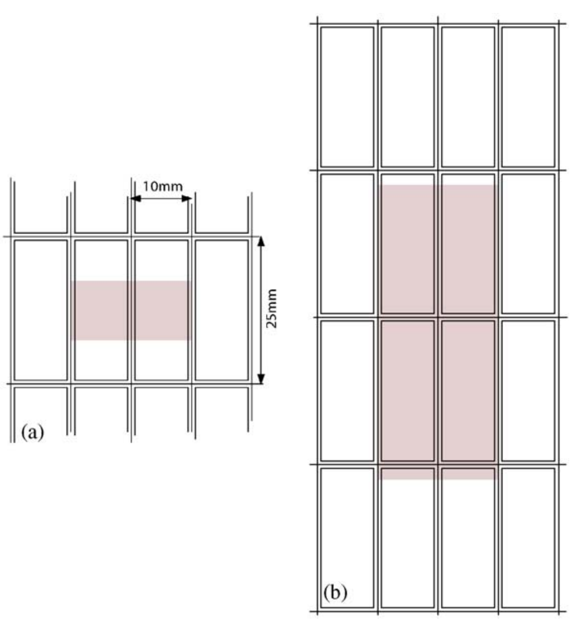

Fig. 11. The selected beam positions for (a) the horizontal and (b) the full cluster size studies.

6. Conclusions

We have tested two different designs of low gain MWPCs for the LHCb muon trigger: an asymmetric MWPC and a symmetric MWPC with double cathode pad readout. The properties of the chamber are well understood. Both double gaps show a robust behaviour; no trips (sparks) were observed in the beam tests up to 2.3 kV (3.35 kV) for the asymmetric (double cathode pad) chamber. We observe comfortable efficiency plateaus. At the working points the time r.m.s. is around 3.75 ns for both, going down below 3 ns at higher voltages. The horizontal cluster sizes are 1.2 (1.4) for the asymmetric (double cathode pad) chamber.

References

[1] LHCb Muon System Technical Design Report, CERN/LHCC 2001-010 LHCb TDR 4, The LHCb Collaboration.
[2] B.Bochine, et al., Wire pad chambers for the LHCb Muon System, LHCb-2000-003-Muon.
[3] M. Hohlmann, Aging problem in wire chambers, Presentation at the Eighth International Conference on Instrumentation for Colliding Beam Physics, 2002.
[4] G. Charpak, D. Rahm, H. Steiner, Nucl. Instr. and Meth. 80 (1970) 13.
[5] E. Roderburg, et al., Nucl. Instr. and Meth. A 323 (1992) 140.
[6] G. Charpak, I. Crotty, Y. Giomataris, L. Ropelewski, M.C.S. Williams, Nucl. Instr. and Meth. A 346 (1994) 506.
[7] E. Christophel, M. Dracos, R. Strub, Nucl. Instr. and Meth. A 454 (2000) 227.
[8] S. Horikawa, et al., Nucl. Instr. and Meth. A 481 (2002) 166.
[9] GARFIELD, Version 7.04, Simulation of Gaseous Detectors, Rob Veenhof, CERN, 2001.
[10] S. Ramo, Proc. IRE 27 (1939) 584.
[11] W.M. Bokhari, et al., IEEE Trans. Nucl. Sci. NS-43 (1996) 1725.