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Section A

Results on Monte Carlo simulations of a microstrip gas counter

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Results from Monte Carlo studies of the operation of a microstrip gas counter are presented. The Monte Carlo was tuned on data from test beam measurements using minimum ionising particles and DME/CO_2 60/40 as a counter gas. We determined the position resolution of the detector for minimum ionising particles in different geometries and as a function of the incoming angle of the particle. It is made plausible that a position resolution of about 20 μm can be obtained by increasing the gas gap and/or reducing the anode pitch. The performance of a thin gap MSGC is also discussed.

1. Introduction

Since its introduction by Oed in 1987 [1], the microstrip gas counter (MSGC) has become a widely investigated particle track detector [2–5]. It is currently used in small-scale applications and it has been proposed as a vital part of the tracking system of various future high energy physics experiments. The MSGC, a miniature variant of the multiwire proportional chamber, can be operated in a fast mode (signal duration 30 ns), in which it can stand fluxes exceeding 5×10^5 $cm^{-2} s^{-1}$ and has a position resolution around 40 μm and 97% efficiency. In experiments that are less demanding with respect to signal speed, the device can be used for position measurements with a resolution better than 30 μm and 99% efficiency.

Test beam studies of the device have so far been concentrated on a prototype with an anode pitch of 200 μm. They showed that minimum ionising particles can be detected with > 95% efficiency and a position resolution around 30 μm [6,7]. In this report, the results of a Monte Carlo study on the efficiency, position resolution and angular dependence of the response of the MSGC are presented, with a drift gas of DME/CO_2 and assuming that no magnetic field is present [8].

Section 2 discusses the effects contributing to the position resolution of the MSGC. In section 3, the Monte Carlo is described. Section 4 deals with the way the Monte Carlo was tuned to test beam results. The results from the simulation are presented in section 5.

2. Position resolution of an MSGC

With an MSGC, the position of a particle is determined as follows. The electrons liberated by the particle drift towards the anode plane and cause a signal on a few anode strips after gas amplification. The position of the track in the direction perpendicular to the strips is then determined by calculating the centre of gravity of the signals from the strips. Assuming that the electronic readout of the detector is perfect, the position resolution of the MSGC is determined basically by five effects:

- ionisation density of the drift gas;
- range of δ-electrons;
- transversal diffusion;
- undersampling of the ionisation cloud;
- gain fluctuations.

2.1. Ionisation density of the drift gas

The ionisation density enters as a determining factor in the statistical contributions to the position resolution (transversal diffusion, gain fluctuations and the occurrence of δ-electrons), and should be as high as possible in most cases. In a gaseous detector one mostly uses drift gases with a high ionisation density (such as noble gases and DME) to obtain large signals and high statistics. DME is the gas with the highest known primary ionisation density (55 cm^{-1} @ STP) and this makes it interesting for the use in MSGCs.

2.2. The contribution from δ-electrons

In general, the electrons liberated by an ionising particle get a kinetic energy in the direction about perpendicular to the direction of the ionising particle. If the energy transfer in the collision is larger than a few hundred eV, the liberated electron will travel a macroscopic distance before it is stopped and the secondary ionisation takes place away from the original track. Such primary electrons are usually called δ-electrons.

For detectors like the MSGC, where the path length of a particle in the drift gas is typically a few mm, the effect of δ-electrons is rather low. The effect of these ionisations to the overall performance of the MSGC is estimated using the formula for the practical range of a primary electron as in ref. [9] and the cluster density distribution as described in section 4. The probability that a liberated electron is a δ-electron with a practical range of > 10 μm is 0.4%.

To estimate the effect of these δ-electrons to the overall position resolution of an MSGC, the projection of all electrons from a minimum ionising particle to the anode plane were considered. The centre of gravity of the group of electrons is dislocated because the clusters are not created exactly along the track. The distribution of the centre of gravity of the electrons along x is non-Gaussian, sharply peaking with a long tail. In a 2 mm gas gap the centre of gravity of the electron cloud is more than 100 μm away from the actual position of the track in 1.2% of the cases. If a few MSGCs are used in a row, such a point will fit badly to the other measurements and can be rejected on those grounds. For a 30 μm resolution MSGC, setting a cutoff at $\pm 3\sigma$ on the δ-electron distribution leads to a rejection of 1.1% of the hits. The contribution from δ-electrons to the position resolution of an MSGC is the rms of the distribution of the centres of gravity of the electron clouds, after imposing the $\pm 3\sigma$ cut. Rejecting all cases beyond ±90 μm the rms of the remaining distribution is 5.7 μm. If the detector reaches a better resolution, the δ-electron tail can again be reduced with a sharper cutoff (only leading to a lower efficiency). (For instance, cutting at ±45 μm yields a 3.3 μm contribution with a 1.7% inefficiency.)

For larger gas gaps, the influence of δ-electrons to both the resolution and the efficiency gets more important. With a 1 cm gas gap, cutting on ±90 μm the inefficiency becomes 4.8% and the rms 12 μm.

2.3. Transversal diffusion

The contribution of the transversal diffusion to the position resolution is (to first order) geometry-independent, and depends only on the drift gas characteristics. This dependence can be intuitively seen as follows. Consider an MSGC-like setup (see fig. 1) with perpendicularly incident particles ($\theta = 0$ in the figure). The position of the track is determined from the centre of gravity of the ionisation cloud. An electron, liberated along the track of the incoming particle at a height h above the anode plane, will diffuse during its drift towards the anode plane. Instead of reaching the anode plane at the position dictated by the field lines in

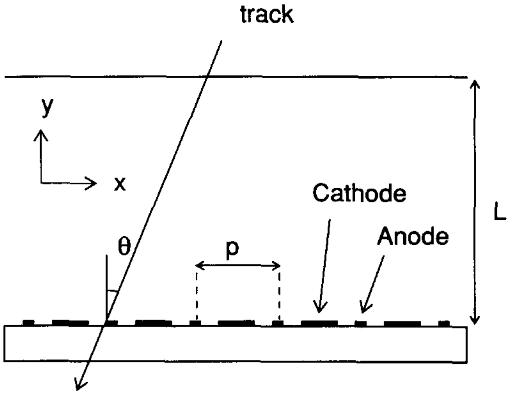


Fig. 1. Geometry of the MSGC.

the detector, it has a probability to hit at a distance r of this position given by the Gaussian distribution

$$P(r, h) = \frac{1}{D\sqrt{2\pi}} e^{-r^2/2D^2}, \quad (1)$$

with $D = \sigma_T \sqrt{h}$, where σ_T is the transverse diffusion, or, in one dimension,

$$P(x, h) = \frac{1}{\sigma_x \sqrt{2\pi h}} e^{-x^2/2\sigma_x^2 h}, \quad (2)$$

with $\sigma_x = \sigma_T / \sqrt{2}$. If we consider one electron released along a track, h is not known. The distribution of single electrons coming from ionisation of a crossing particle can be found by integrating eq. (2) to h, with h running over the length of the track L. The resulting distribution shows a Gauss-like curve with a sharp peak and a long tail (fig. 2 shows its shape as generated by a Monte Carlo simulation). The rms of this distribution is approximately

$$\Delta x \approx \tfrac{1}{2} \sigma_T \sqrt{L}. \quad (3)$$

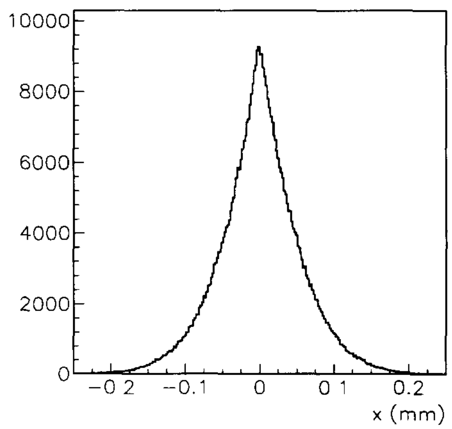


Fig. 2. Distribution of electrons along the x-direction after drift and diffusion, for a 5 mm gas gap and $\sigma_T = 50$ μm/$\sqrt{\text{mm}}$.

Table 1
Diffusion contribution to resolution for various gas mixtures. The values of the transversal diffusion for a certain electric field strength E are from the references in the table

Gas mixture		σ_T [μm/ $\sqrt{mm}$]	@ E [kV/ cm]	Δx_N [μm]	Ref.
Ar/C_2H_6	63/37	247	0.60	38	[10]
CH_4/C_2H_6	80/20	110	0.70	21	[11]
Xe/CO_2	95/5	163	0.20	15	[12]
$Xe/DME/CO_2$	30/30/40	62	8.0	7	from MC
DME/CO_2	60/40	50	8.0	7	from MC

This value is the same as the rms of the position distribution of electrons liberated at $h = \frac{1}{2}L$. The dependence on L cancels if we consider N electrons distributed homogeneously along the track of the incoming particle. A crossing minimum ionising particle will on average ionise $N = n_T L$ gas molecules, where n_T is the total ionisation density. Therefore, the rms of the distribution of these N electrons on the anode plane can be written as

$$\Delta x_N \approx \sigma_T / 2\sqrt{n_T}. \tag{4}$$

Essentially, this means that if the gas gap is increased, the cloud width becomes larger, but the improving electron statistics make that the spread in centre of gravity remains the same. In practice, N varies statistically from event to event and the electrons are not distributed homogeneously, but the replacement of N by $n_T L$, as in eq. (4), holds when N is large. If N is small (< 100), Δx_N is higher than eq. (4) would suggest.

Eq. (4) gives us the contribution from the diffusion to the position resolution. Note that this term only depends on drift gas properties. The value of Δx_N for a few drift gas mixtures is listed in table 1. The table includes σ_T for $Xe/DME/CO_2$ and DME/CO_2; both values are determined by fitting the Monte Carlo results with the charge distribution data from our measurements.

From the table it can be seen that the position resolution of an MSGC can be affected by a bad choice of the drift gas. To achieve a resolution of the order of 30 μm, a drift gas with high ionisation density and low transversal diffusion should be chosen. The $Xe/DME/CO_2$ and DME/CO_2 gas mixtures have extremely good n_T and σ_T. Therefore, if one of these mixtures is used, the position resolution of an MSGC will be dominated by other effects.

2.4. Undersampling

Undersampling of the electron cloud takes place when the pitch p of the anode structure is too large compared to the size of the electron cloud. For $p \ll \Delta x$ (see eq. (3)), the cloud is effectively sampled. When $p \approx \Delta x$, systematic deviations occur in the measured position of the track. In the case that $p \gg \Delta x$, generally only one anode gives a signal when a particle crosses, and the position resolution is given by $p/\sqrt{12}$.

2.5. Gain fluctuations

Fluctuations in the gas amplification confuse the determination of the centre of gravity of the electron cloud, and therefore contribute to the position resolution of an MSGC. If undersampling of the electron cloud can be avoided, the diffusion error and gain fluctuations are in practice the most important contributions to the position resolution.

There seem to be two ways to achieve the optimum resolution in an MSGC: a thin gap (L of the order of 2 mm) detector must have a very low pitch and minor gain fluctuations. In a large gap ($L > 1$ cm) detector the requirement of small gain fluctuations can be loosened because the number of electrons is larger. The pitch can be larger because the electron cloud is broader. The occurrence of δ-electrons increases with L and this will add to the position measurement error.

Probably the best way to suppress the problems associated with low electron statistics is to improve the ionisation density along the y direction either by pressurising the drift gas or by tilting the detector such that the particle trajectories run along the anodes. Pressurising the drift gas has as an additional advantage that the range of δ-electrons becomes smaller.

3. General description of the Monte Carlo simulation

As compared to a multiwire proportional chamber, the MSGC has a much smaller anode pitch and gain fluctuations are at a low level. Therefore, one can expect the detector to have a very good position resolution. To find out which of the above mentioned effects dominate the position resolution of the MSGC, a Monte Carlo program has been written which simulates the generation of ionisation, transverse diffusion and the gas amplification process. No magnetic field was implemented and the electric field is perfect (no edge effects etc.).

The program simulated the MSGC in the following way: in a given geometry, a particle crosses the detector under a given angle θ with respect to the normal of the strip surface. A two-dimensional model of the MSGC is used (see fig. 1), because the coordinate parallel to the strips is of no significance to the response of the detector [#1].

[#1] This holds as long as the ionizing particle runs perpendicular to the strip direction, otherwise the path length inside the detector increases.

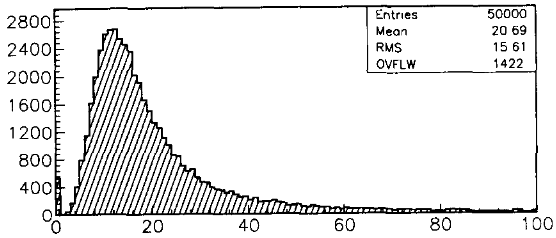


Fig. 3. Total ionisation spectrum in a typical MSGC using DME/CO_2 60/40 with an estimated cluster size distribution (see text).

A minimum ionising particle traveling in the (x, y) plane under an angle θ causes a number of primary ionisations N_p which is Poisson distributed. Each primary electron can in turn ionise some more molecules, leading to a total ionisation of N_T electrons, grouped in N_p clusters of electrons. (The electrons created in the quadrupole field near the strips are treated in the same way as those liberated in the drift field.) In the simulation, these clusters are pointlike and occur exactly along the track.

From their starting point, the electrons will drift towards the strip plane, while they undergo a displacement in x because of transverse diffusion. When the electrons reach the quadrupole field (at a height above the strip plane roughly equal to the pitch of the strip pattern) they will be focused towards one of the anodes. This electrostatic focusing makes the probability very low that a drifting electron will jump to an adjacent anode. Therefore the diffusion is switched off in this region.

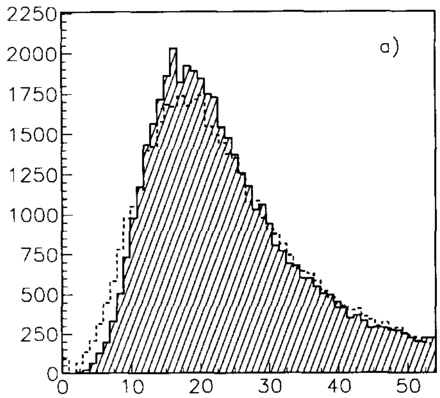
To simulate the contribution of each electron to the signal on the strip, it is attributed a "gas gain" of 1.0 (the units are arbitrary) on average, on which a statistical fluctuation is imposed. The signal from a strip is taken into account when it comes above a threshold, which was set to 1.9 electrons (unless otherwise stated).

4. Tuning the Monte Carlo to experimental data

A beam test performed in June 1991 provided us with adequate data for tuning the Monte Carlo program, with respect to the diffusion, the gas gain and fluctuations. The experimental setup consisted of 4 MSGCs in a row, with in total 60 channels read out. Most measurements were performed using DME/CO_2 60/40 as a drift gas; the anodes were grounded, the cathode strips were set at -720 V, and the cathode plane (at a height $L = 2.8$ mm) was set to -2730 V. The anode pitch was 200 μm. To determine the position resolution of this configuration independently of systematic effects, a fine angular scan was performed [7].

In principle one should use the statistical distribution of the number of electrons in a cluster to simulate the ionisation process. For DME this distribution is not known; data for CO_2 are given in ref. [13]. A first-order approximation is made for the mixture DME/CO_2 60/40. The probability to find n electrons in a cluster is $w(n)$. From theory it follows that $w(n)$ goes as $1/n^2$, apart from deviations at small n that depend on atomic properties of the gas molecules. From experiments it is known that $w(1)$ is around 0.70 for most gases (see ref. [13]).

In the simulation, $w(1)$ was set to 0.70, and $w(n) \sim 1/n^2$ for $3 \leq n \leq 1000$. The distribution of $w(n)$ should be normalised to 1 so there is one free parameter left. This parameter, $w(2)$, can be determined using the border condition that the average cluster density should be $\langle n \rangle = n_T/n_P$. DME/CO_2 60/40 has a primary ionisation density $n_P = 46.6$ cm^{-1} and a total ionisa-



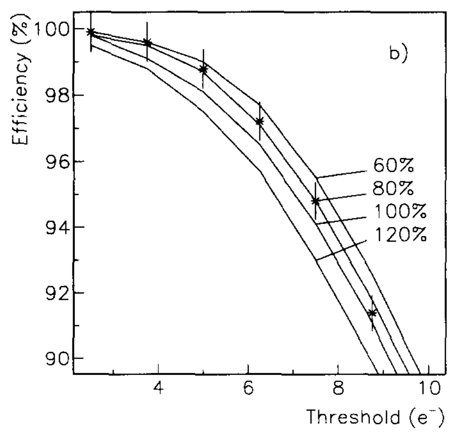


Fig. 4. (a) Calculated signal from an MSGC assuming very low gain fluctuations (hatched histogram) and high gain fluctuations (dashed line). (b) The calculated efficiency of an MSGC as a function of the applied threshold for different values of the gain fluctuation rms; as a comparison, a few measured points are plotted from the beam test.

tion density $n_T = 126$ cm^{-1} assuming a total ionisation density of 150 cm^{-1} for pure DME. This yields $w(2) = 0.17$. This cluster density distribution leads to a total ionisation spectrum as shown in fig. 3. The plot was made for a track length of 2 mm.

For reasons of simplicity the amplitude curve of the MSGC to single electrons is assumed to be Gaussian. This leads to only one parameter to fix: σ, or the standard deviation normalised to the mean value σ/μ. This parameter can be found by matching the simulated Landau distribution to the Landau distribution measured during the beam test. The shape of the Landau curve is influenced by the gain fluctuations: the higher the fluctuations, the more the steep edge (at low values) will be flattened. This behaviour is demonstrated in fig. 4a, which shows the amplitude curve of minimum ionising particle signals in a 2.8 mm MSGC assuming Gaussian gain fluctuations with $\sigma/\mu = 0.10$ (hatched histogram) and $\sigma/\mu = 1.0$ (dashed line). This effect can be used to make an estimate of the size of the gain fluctuations in an MSGC. In fig. 4b, the number of hits is plotted, as a function of the applied threshold, for different values of σ/μ. As a comparison, in the figure a few points as measured in our beam test are also plotted. It is clear that for the low end of the gain fluctuation distribution, the Gaussian approximation holds well if single electrons have a response with a sigma around 80% of the mean value.

With this calibration of the gain fluctuations, the program can be used to predict the efficiency of the device at different values of the gas gap width, and as a function of the incoming angle of the track.

Electronic noise was implemented as uncorrelated with a a of the equivalent of 0.5 e$^-$ in the simulation. Crosstalk was not implemented.

5. Predictions on the performance of the MSGC

5.1. Introduction

The simulations done were restricted to the operation of the MSGC with DME/CO_2 60/40, at the operating voltages mentioned in the previous section. The results presented here are centered around two "balanced" detector geometries: one with an anode pitch of 200 μm and a 5 mm gas gap, and one with $p = 150$ μm and $L = 2$ mm. It is clear from section 2 that the dimensions chosen for the detectors which have been tested in a beam ($p = 200$ μm, $L = 2.8$ mm and $\sigma_T = 50$–60 μm/$\sqrt{\text{mm}}$) lead to undersampling of the electron cloud. Thus, a better position resolution than measured can be expected by either increasing the gas gap or reducing the pitch. The dependence of the position resolution on the gas gap width L and the angle of incidence θ are discussed in section 5.2; section 5.3 deals with the position resolution as a function of the pitch. The performance of a thin-gap MSGC is addressed in section 5.4.

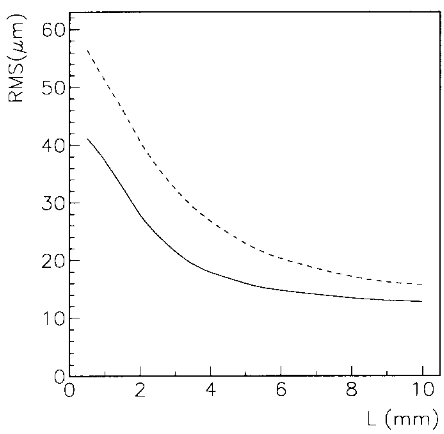


Fig. 5. The position resolution of an MSGC as a function of the gap thickness L with $p = 150$ μm (solid line) and $p = 200$ μm (dashed line).

The position resolution of the MSGC at a certain geometry is calculated as follows. Each of 20000 minimum ionising particles is sent through the detector, the liberated electrons giving rise to a signal on a few strips. For all strip signals passing the threshold, the centre of gravity is calculated, and related to the actual track position. To obtain the correct contribution of the systematic effects, the particles were distributed homogeneously over one period of the strip pattern.

5.2. The position resolution versus the gas gap width and angle

The outcome of the Monte Carlo showed that the position resolution of an MSGC depends very strongly on the width of the gas gap. This is shown in fig. 5 for two different values of the anode pitch. The figure indicates that the position resolution of 30 μm measured in two beam tests [3,7] is not a constant but is strongly dependent on the geometry chosen.

The efficiency for perpendicular tracks increases with the gas gap width. Therefore, it is clear that for an optimal resolution and efficiency, one should aim for a maximal gas gap. Unfortunately, when using a large gap the duration of the signal from the detector (determined by the drift time of electrons in the detector) increases, and also the resolution will be more affected at small angles of incidence. The latter effect is demonstrated in fig. 6 for a thin-gap and for a large-gap detector. At small angles of incidence the large-gap detector performs better, but above 2° its resolution rapidly deteriorates.

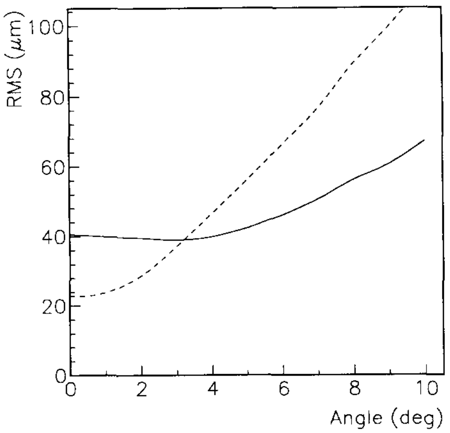


Fig. 6. The position resolution of an MSGC as a function of the angle of incidence of the ionising track, for an MSGC with 2 mm gas gap (solid line) and in case of a 5 mm gas gap (dashed line), both with a 200 μm pitch.

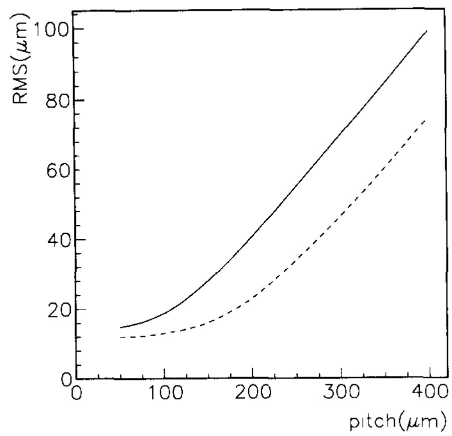


Fig. 7. The position resolution of an MSGC as a function of the anode pitch for an MSGC with $L = 2$ mm (solid line) and $L = 5$ mm (dashed line).

In the same figure, another effect of undersampling can be seen. The detector with the 2 mm gas gap has a slightly better resolution for particles incident under small angles, than for perpendicularly incident particles. Here the transversal diffusion does not distribute the electron cloud sufficiently to avoid undersampling. If the track goes under a small angle the ionisation is spread more along x because of the increasing projection of the track to the strip plane, leading to a better position determination.

5.3. The position resolution versus the anode pitch

Reducing the anode pitch can also lead to a significant improvement of the position resolution of the MSGC. This is shown in fig. 7 for two different values of the gas gap width. However, one should remind that at very low pitch, the gas gain might not be kept at a reasonable level. Also other effects that were not incorporated, could become important for resolutions below 20 μm. Nevertheless, the graph is instructive in showing how important pitch reduction is. The 13.4 μm resolution predicted by the Monte Carlo for a 50 μm pitch MSGC with 2 mm gas gap, consists of the following contributions:

- 9.6 μm from transversal diffusion of the electrons;
- 7.4 μm from gain fluctuations;
- 4.3 μm from electronic noise;
- 3.7 μm error from undersampling.

As stated before, δ-electrons give an estimated 3.3 μm contribution, if more MSGCs are used in a row and 1.7% inefficiency can be tolerated. Other contributions to the error which were taken into account, such as from the rejection of signals below threshold, are negligible. Note that the non-Gaussian behaviour of the actual single electron response may lead to a significant increase of the contribution of the gain fluctuations to the position resolution.

5.4. Optimisation of the MSGC for LHC

The 15 ns bunch crossing frequency at the LHC asks for a fast response of the involved detectors. The pulse duration of the MSGC is dominated by the drift time of the electrons in the gas gap. The drift velocity is in practice limited to 60–100 μm/ns. Therefore the gas gap width of the device should not exceed 2 mm if the pulse should not cover more than two bunch crossings. Using fig. 7 for a certain resolution the required pitch can be found. Fig. 8 shows that using a low threshold, the efficiency can be 99% even with a 2 mm

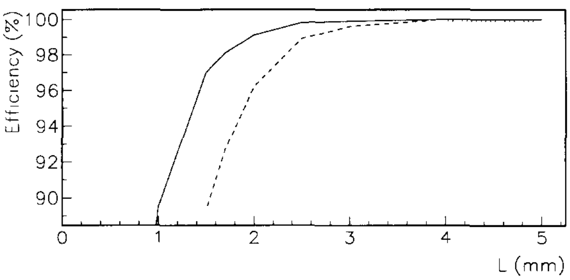


Fig. 8. The efficiency of a 200 μm pitch MSGC as a function of the gas gap width L, with a threshold on the highest strip of 1.9 electrons (solid line), 3.8 (dashed line) and 5.7 (dotted line).

gas gap, provided that the background noise permits such a low threshold level.

In practice, other phenomena than a low pulse height will contribute to the inefficiency. To achieve an acceptable resolution, δ-electron events must be cut leading to an additional inefficiency of the order of 1%. Furthermore, it is obvious that in practice dead electronics channels, broken anodes etc. will add to the effective inefficiency of an MSGC.

6. Conclusions

With a rather simple approximation of the ionisation and gas amplification process, the efficiency and position resolution of the MSGC as a function of incoming angle, gas gap width and pitch are successfully reproduced. The detector can be optimised for high-speed (30 ns) performance. The simulation program predicts such a device to have a position resolution around 40 μm with an efficiency of 97%. This can be done using a 2 mm gas gap and a drift gas with a high drift velocity. The position resolution can be improved by decreasing the anode pitch.

The detector can also be optimised for high-accuracy and high-efficiency applications, with a predicted position resolution around 20 μm for perpendicularly incident tracks and 99% efficiency. This is achieved by using a large gas gap and a drift gas with high primary ionisation density and low transversal diffusion.

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