A How-to Approach for a 3d Simulation of Charge Transfer Characteristics in a Gas Electron Multiplier (GEM)[1]

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Abstract

In this paper a detailed description of how to simulate charge transfer processes in a gaseous device is presented, taking the Gas Electron Multiplier (GEM) as an example. A 3-dimensional simulation of the electric field and avalanche is performed. Results on charge transport are compared to experiment and agree within experimental errors; avalanche mechanism and positive ion feedback are studied. The procedures used in the simulation are described in detail, and program scripts are appended.

1. Introduction

The simulation of the performance of gaseous detectors has been intensively developed in the last decade. The main tool to study electrostatic properties of wire chambers - GARFIELD has been extended into 3-dimensions [1] with the inclusion of planar geometry, for example a drift tube with a cylindrical cathode is approximated by a polygonal tube with several sides. Nevertheless, there are limitations and odd shaped electrodes, occurring more frequently in novel gaseous detectors, are not permitted and neither are dielectrics materials. This is made possible by using commercial packages like MAFIA [2] or MAXWELL [3], which deal with all sorts of geometry and materials. The intensively developed gas transport parameters simulation, MAGBOLTZ [4], has been integrated into GARFIELD; interface with HEED [5], a program specifically developed for energy loss of charged particles, cluster characteristics, range and straggling of delta electrons and photoionization, has also been integrated. Thus a complete simulation of charge transfer: drift, diffusion and multiplication of electrons in the detector and subsequent signal generation, positive ion movement can be performed.

In this paper we will try to show how to compute the electrostatic fields in a 3-dimensional model for a micro-pattern detector, the GEM, in MAXWELL, then import the field into GARFIELD and subsequently generate electrons and follow their paths, while they drift, diffuse and multiply in the electric field [6]. In a GEM, taken as an example, among other characteristics it is important to know what is the electron transfer efficiency of the foil. The tools developed in conjunction with the aforesaid programs have been quite useful in computing and comparing with experiment, thus lending reliability to the predictive power for other applications.

Since the invention of the Micro-Strip Gas detector, over the last decade a variety of micro-pattern detectors [7] have invaded the scene of charged particle tracking in a hostile high luminosity environment replacing the traditional multiwire chambers with their higher rate capability. Made with simple printed circuit board technology, with through holes etched on double sided metallized Kapton foils typically 50 μm thick, the GEM [8] has been demonstrated to be a robust charged particle detector. Two foils in cascade form a Double GEM [9-11], delimited by a drift electrode above the first foil and a signal collection electrode below the second. Due to its design, positive ion feedback into the drift is reduced as compared to that of a wire chamber [12].

Here the electron drift properties are investigated and transparency has been computed and compared to experimental results; gain and positive ion feedback are also estimated.

2. Description of the problem

Ansoft's 3D Field Simulator (3DFS) is an electromagnetic Finite Element Method (FEM) solver [3]. It allows designers to experiment with various three-dimensional geometry, materials and excitation levels (voltages). The program can be used to solve electrostatic, magnetostatic and AC magnetic problems. The

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electric fields and potential gradients are solved for complex systems of conductors, charges and dielectrics. The software includes a solid modeller that allows a three-dimensional representation of the device or structure to be analysed. Once drawn, the materials and boundary conditions can be specified. A finite element mesh is automatically generated, eventually refined by the system/user and the problem solved yielding fields and potentials in the whole volume.

The GEM amplifies electrons released in a gas by ionising radiation. With appropriate potentials on the drift electrodes and across the GEM, and a grounded collection electrode, electrons enter the drift volume and are multiplied in the high electric fields in the GEM channels (E_H). The resulting avalanche of electrons provides sufficient gain for charged particle detection. To better understand their performance, simulation studies were started with 2D models [13]. These were limited by the fact that the behaviour of the fields and potentials in regions between three adjacent holes could not be predicted or estimated, thus giving only a qualitative picture of the drift and multiplication properties of GEM. The geometry used throughout this work is as follows unless stated otherwise: 70 μm metal hole diameter, 50 μm Kapton diameter and 140 μm pitch with staggered rows.

The question now is how to describe the GEM geometry in the 3DFS, so that the computed electric field has sufficient accuracy and can be used predict an electron's path as well as the avalanche multiplication mechanism in the real structure. The GEM structure modelled in this problem is shown in Fig. 1. The structure consists of a double-sided metallized Kapton dielectric, where holes have been etched, using a staggered array to maximise the channel density and optical transparency. Full transparency – or transmission of all electrons such that none are trapped on the top (or bottom) metallic surface – is one of the key design issues of the GEM. The inherent periodicity and symmetry of the structure should be exploited while making the model. There are several options while choosing the basic repetitive cell (see Fig. 2).

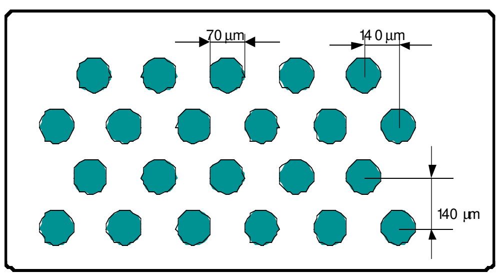

Fig 1. Basic GEM structure

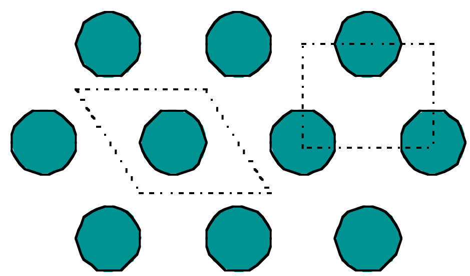

Fig 2. Possible GEM basic cell definition

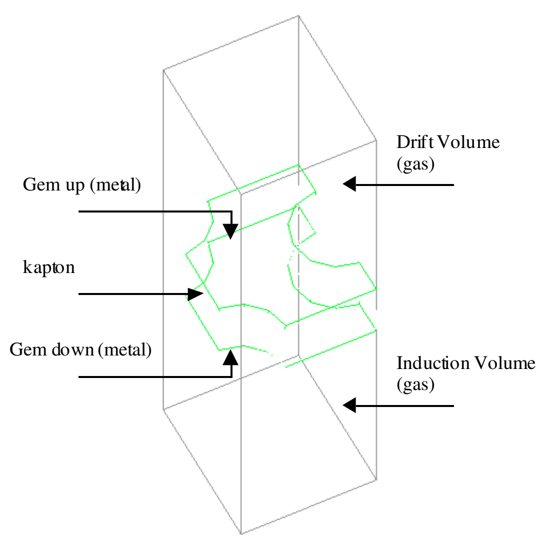

Fig 3. GEM 3D model: materials & volume description

One of the most important parts of the design with the 3DFS is the use of the CAD program for the structure description. This stage is time-consuming for the designer, as the complexity of these 3D objects is high. Also, changing any given dimension often means a tedious and long re-design process.

In order to avoid these problems, a new methodology was explored in this project. It comprised using the new scripting language from Ansoft to create a valid 3D model automatically. The main advantage of this approach is that, once the script is programmed, any change can be easily inserted and the full model automatically recreated. A sample script for creating a basic GEM model is shown in Appendix 1. The new scripting language was studied and a first valid model was produced [15]. Thus, changing some of the dimensions became a trivial task and structural optimisations could be performed. The modelled 3D structure of GEM is presented in Fig. 3.

Once the basic cell is chosen, the model should be drawn in the 3D modeller and solved.

3. Problem solution in the 3D Field Simulator.

Both basic repetitive cells were examined in the 3DFS. The first one, shown in Fig. 2, uses the basic hole with the 60 degrees lines. The materials were defined and the boundary conditions declared. However, there is a problem with the boundary conditions in this case, due to the dual-periodic nature of the structure. This led the simulator to compute the fields rather inaccurately, and the ensuing solutions were invalid. The second basic cell, also shown in Fig. 2, describes the problem differently. The four planes are parallel in this case, and thus the normal component of the electric field will always be null. With this knowledge, symmetry planes can be easily declared in the boundary manager and the solution can be computed accurately.

3.1 Setting the materials and boundaries.

In order to specify the problem, the materials must be assigned. The properties of the dielectric (permitivity, conductivity) and of the metals allow the software to compute the electric fields. There are several predefined materials which can be assigned to the solids in a model defined in Maxwell; see Table 1. In addition one can even define a new material given the permittivity and conductivity. Once this is done, the boundary assignment takes place. This includes the assignment of voltages to both metal planes, as well as the drift and ground potentials. In addition to these potentials, the four symmetric faces should be properly specified here, in order to model the infinite "sea of holes" GEM structure. Figure 4 shows this boundary assignment.

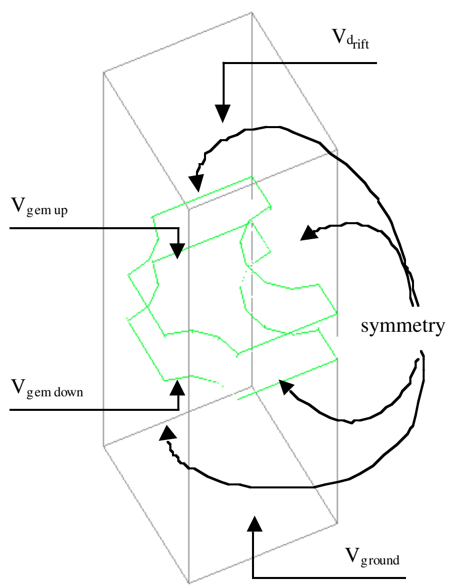

Fig.4 Boundary Definitions

3.2 **Manually refining the 3D mesh.**

One of the problems while solving the model is that the automatically generated mesh is not properly defined in some of the regions where a good field solution is needed, i.e. close to the metal surfaces of the GEM hole. This can be tackled by manually refining the mesh in some volumes in the structure, as follows. Additional dummy objects are included in the definition of the structure. These dummy objects help to refine the initial mesh and increase the solution accuracy. Fig. 5 shows the initial mesh, while Fig. 6 shows a manually refined mesh.

Now the model is ready to be solved.

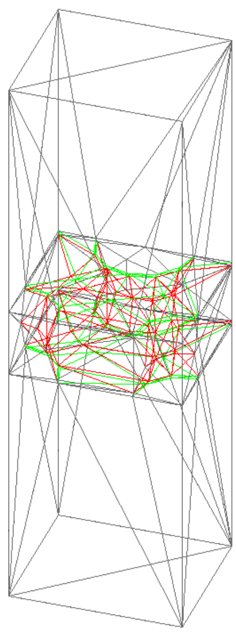

Fig. 5 Initial Mesh

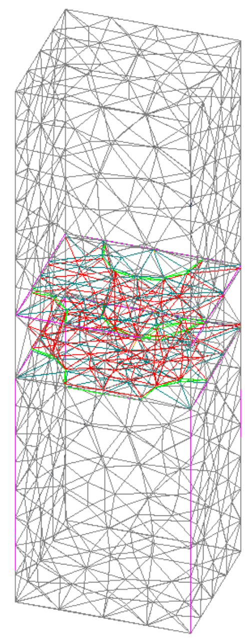

Fig. 6 Manually refined mesh

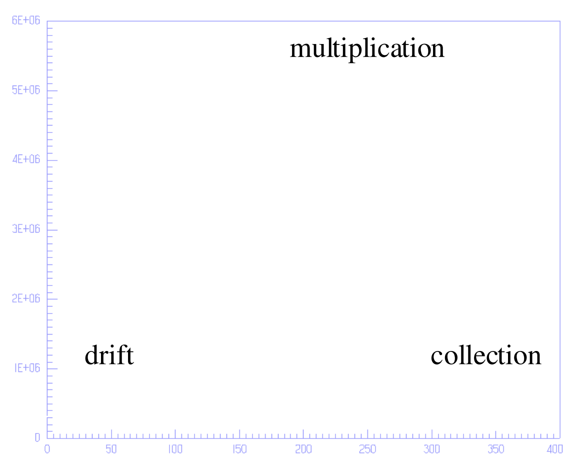

Fig 7. Electric field (V/m) through the GEM hole.

3.3 Solutions

Figure 7 shows the magnitude of the electric field in a line running across the centre of the GEM hole, showing that high values present in this area will create the electron acceleration and multiplication – resulting in an avalanche effect . Figure 8 shows the distribution of the equipotential lines and a vector plot of the electric field in a given plane that cuts the centre of the basic hole.

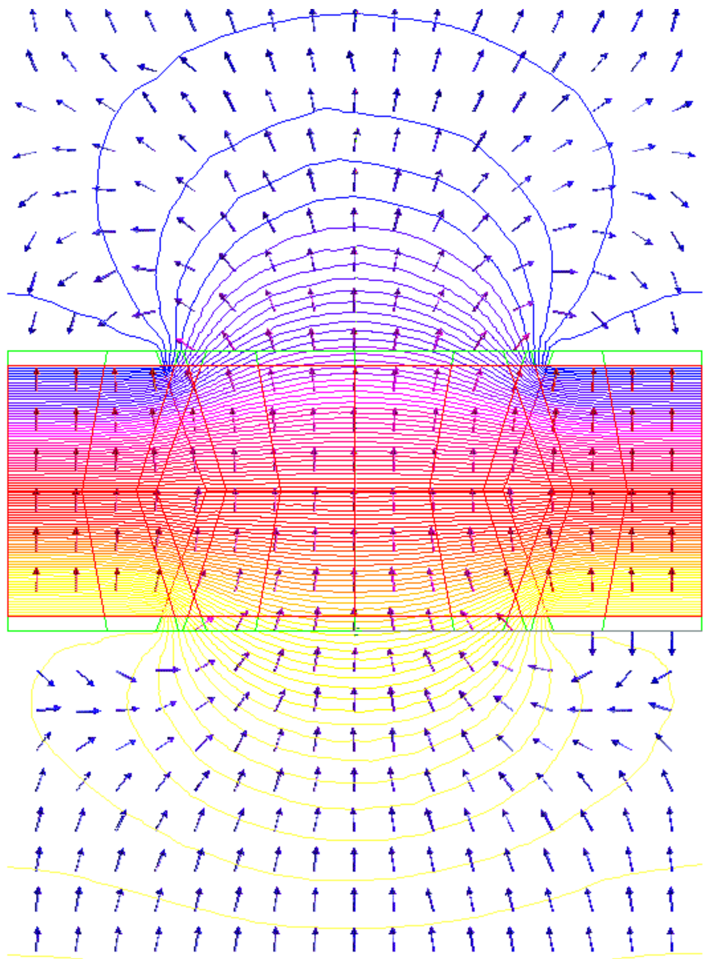

Fig. 8 The distribution of the equipotential lines and a vector plot of the electric field in a given plane that cuts the centre of the basic hole.

4. Importing the field into GARFIELD

Once solved, the output from the MAXWELL may be written out and read into GARFIELD [9] in several files which describe the potentials, electric fields and the materials of the problem at every node of the mesh of the numerous tetrahedra. Appendix II shows an example file, performing the following tasks:

- read the electric field, voltages and materials
- introduce the desired gas mixture
- plot field vectors in a given area or surface
- plot drift lines
- follow each electron with drift and diffusion and compute the end-points
- introduce multiplication and follow the paths of electrons and ions till their end-points.

The field computed by using the 3D model differs from that of the 2D as exemplified in Fig.9 This is due to the metallic surfaces present both on top and the bottom of the GEM unaccounted for in the 2D model, as well as the double conical Kapton well on either side. Figure 10 shows drift of electrons created by a track; one can appreciate the 3D nature of the problem, observing that some of them go into neighboring staggered holes.

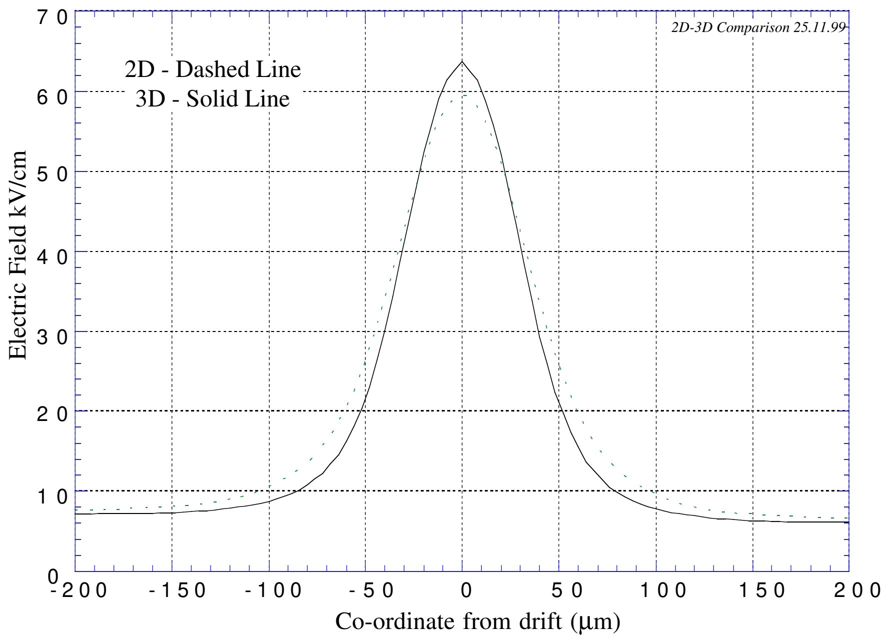

Fig. 9 The field computed using the 3D model differs from that of the 2D calculation.

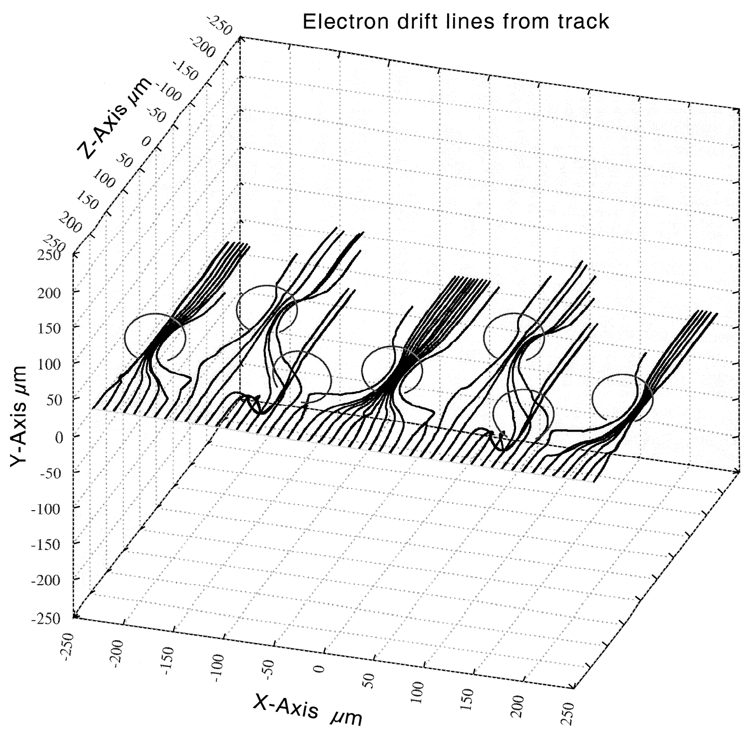

Fig. 10 The plot shows drift of electrons created by a track.

4.1 Transparency of the GEM

More than on individual fields, the electrical transparency of the GEM depends on the ratio of drift to the dipole field (E_D/E_H), and its optical transparency [8]; a staggered matrix increases transparency as compared to straight rows of holes. Within the 3D model, transparency has been computed generating uniformly a matrix of 2500 electrons on the drift electrode surface and following their path as they drift and diffuse down the channel[3]. Figure 11 shows the computed versus measured transparency for a single GEM. The experimental values fall between those computed for holes with 70 µm and 80 µm diameter. This could well [illegible] 'erance of the manufacturing process. Calculations for transparency in a non-zero magnetic field [illegible] esented in section 4.

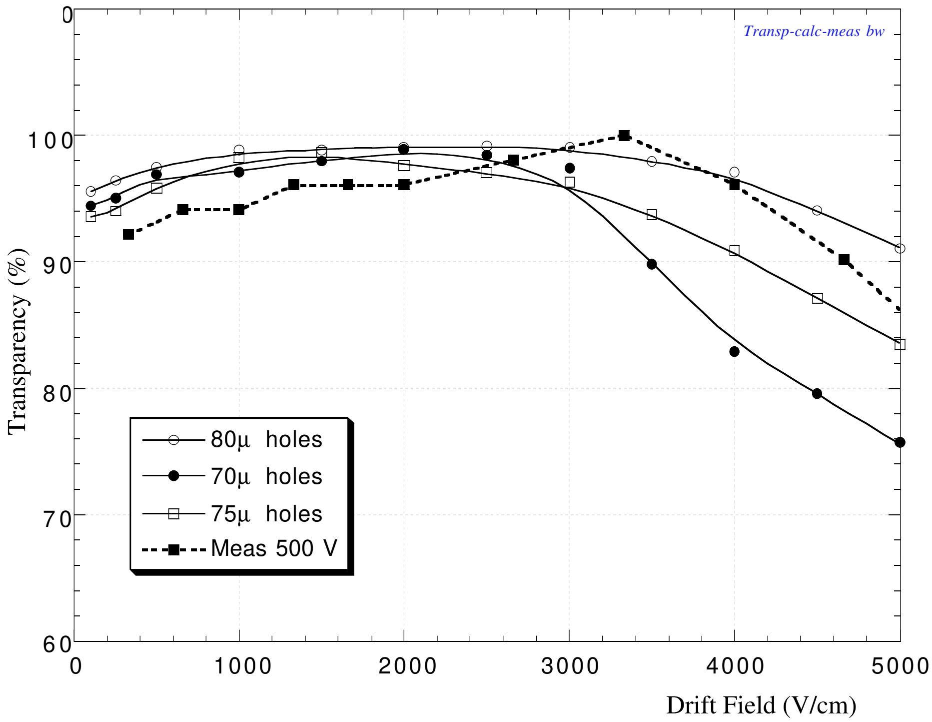

Fig. 11 Computed versus measured transparency for a single GEM.

4.2 Avalanche, Effective Gain and Positive Ions

The previous sections described how electrons move from the drift region into the GEM channels, and accounted for the loss of the electrons simply due to drift and diffusion. When electrons encounter the high field in the holes, they experience ionizing collisions thereby resulting in an avalanche of electrons, whose size depends on the dipole field. Some of the electrons of the avalanche are lost to the bottom electrode of the GEM, as seen in Fig.12, consequently the 'effective' or visible gain of the multiplier is lower than thetotal number of ionizing collisions effected by a single electron [5]. The reliability of computations in thisrespect is quite low, since the Townsend coefficient is not very well known at high fields [10]; gains obtained from calculations differ up to factors of 2-3 when increasing the GEM voltage, as shown in Fig.13. Detailed understanding of this discrepancy is being studied. The majority of the electrons are

[3] The Monte Carlo version of electron drift was used in Garfield.

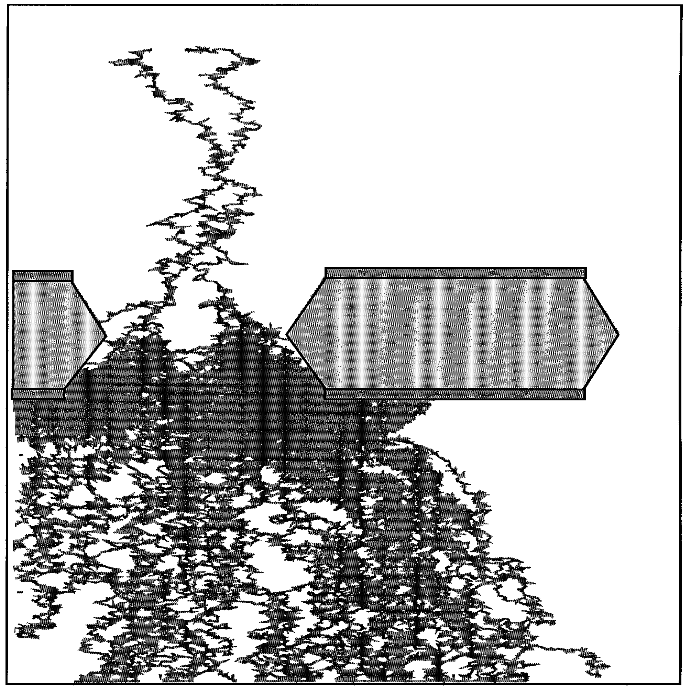

Fig. 12. Some of the electrons of the avalanche are lost to the bottom electrode of the GEM.

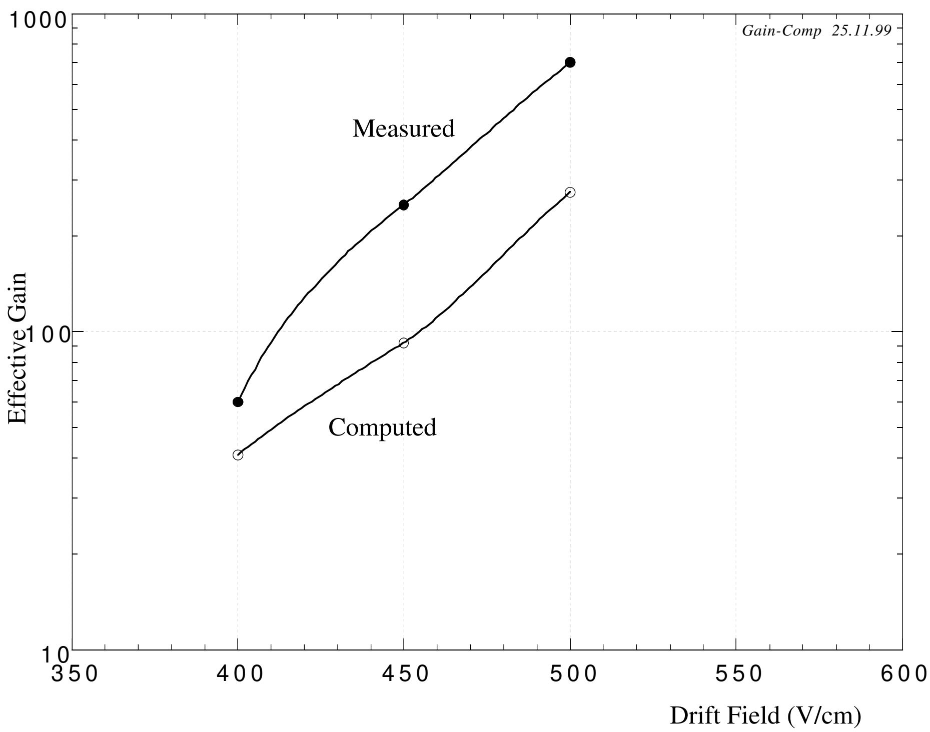

Fig. 13 Gas gains obtained from calculations differ up to factors of 2-3 when increasing the GEM voltage.

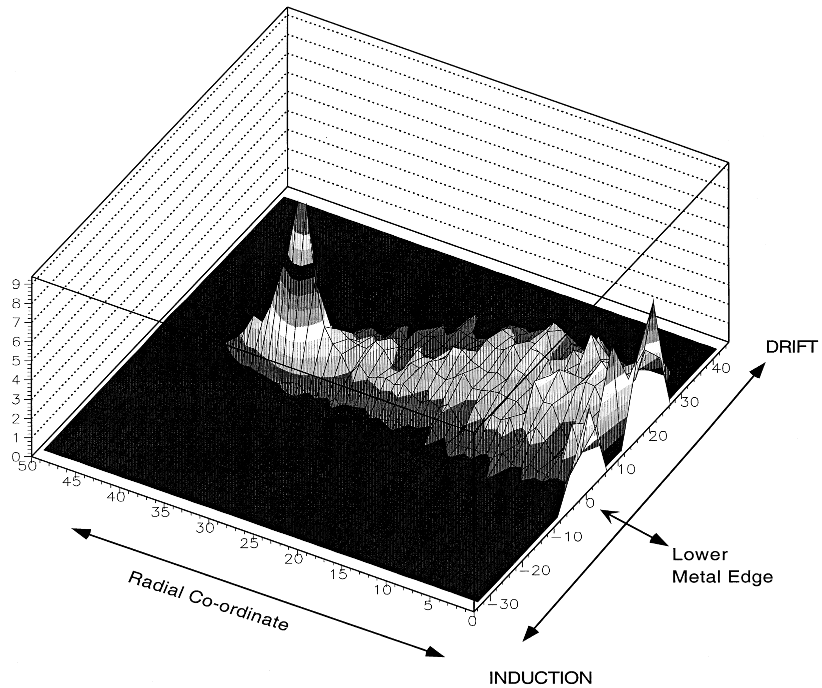

Fig. 14 The majority of the electrons are produced in the center.

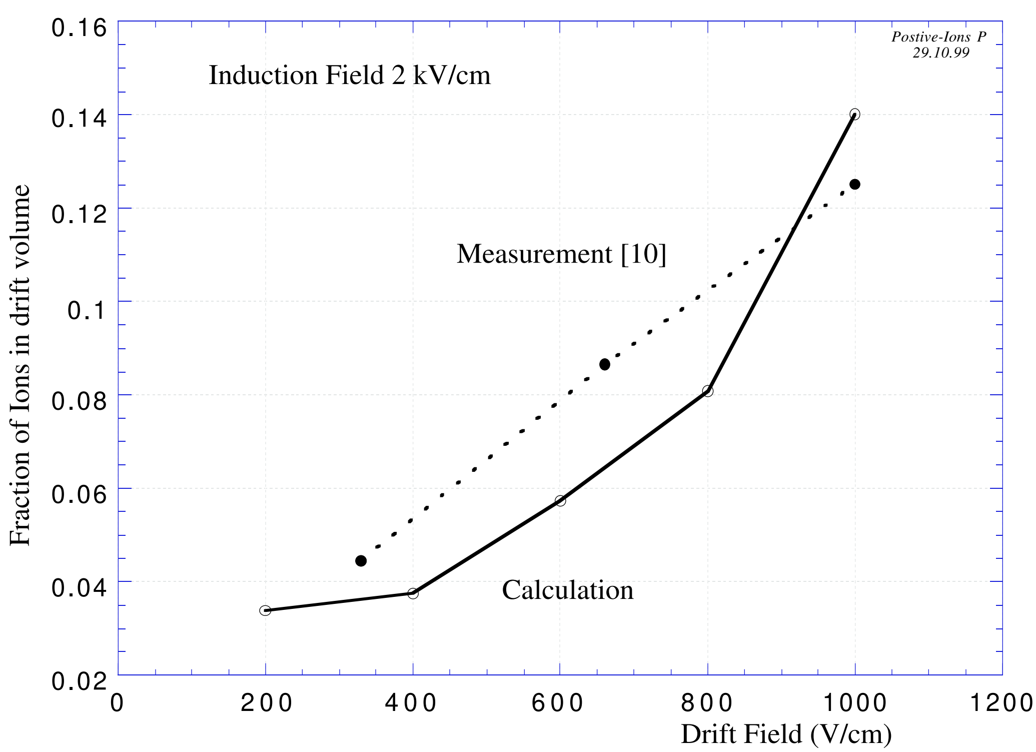

Fig. 15 . The fractional number of positive ion feedback was also verified for a couple of voltage settings points at low drift fields, in general the agreement with [8] is within 20%.

produced in the center; a doughnut of electron production is seen at the lower metal edge Fig. 14, where the electric field is higher. This is a totally local effect; diffusion completely overtakes the field structure in GEM and ~ 200 μm below the GEM surface there is no trace of this effect; thus obliterating the GEM structure for any localization measurements. This results in making the mechanical alignment between two foils (Double GEM) redundant. Positive ions are produced essentially in the whole channel but mostly in the vicinity of the lower GEM electrode; and move to the drift volume, the fraction depending strongly on the drift field [10]. It should be noted however, that the signal detected on readout (strips/pads) is totally due to electron collection, there is no slow component due to the positive ion movement as compared to a traditional MWPC sense wire signal. The time taken by the positive ions to reach the GEM top typically corresponds to a few μs and few tens of μs to reach the drift electrode. The fractional number of positive ion feedback was also verified for a couple of voltage settings points at low drift fields, in general the agreement with [8] is within 20%, as shown in Fig.15.

4. Operation of GEM in a high Magnetic Field

The qualitative behavior of performance in the presence of a strong electric field perpendicular to the drift field was investigated with the 2D model [10]; see Fig.16. Despite several drift lines ending on the bottom of the foil, the lateral spread of the avalanche is enough to compensate for the loss of electrons due to the Lorentz force. Fig.17 shows the computed transparency and gain as a function of magnetic field (perpendicular to the electric field) with an Ar-CO_2 (70-30) gas mixture, and the electric field values as shown in the inset. One can see that while transparency drops dramatically, (note that for these computations, a low drift field was chosen); there is no perceivable effect on the gain; measurements reporting no efficiency drop in the presence of a magnetic field have been published earlier [4]. The gas mixture as well as field configuration is by no means optimized; more work is needed in this direction.

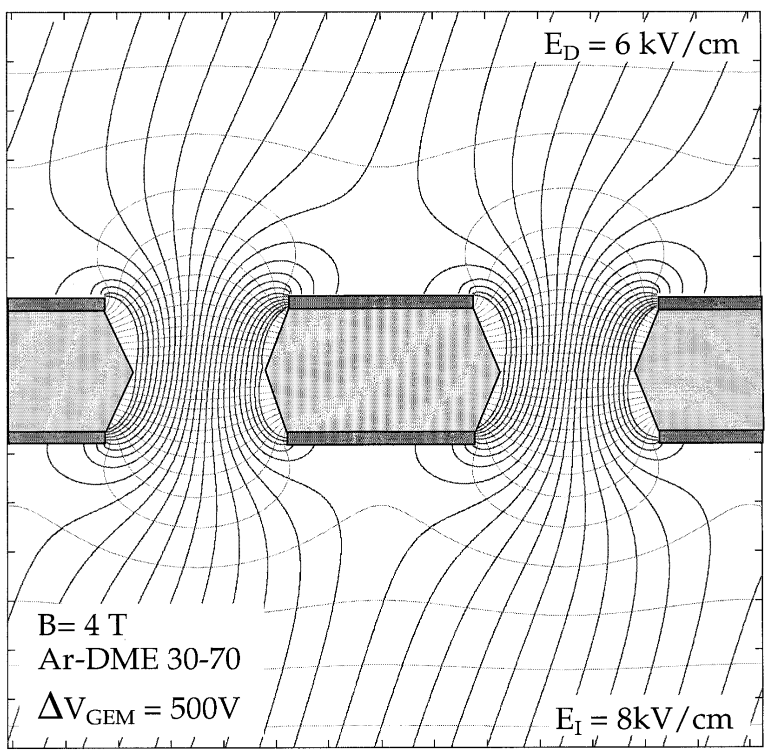

Fig. 16 The qualitative behavior of performance in the presence of a strong electric field perpendicular to the drift field was investigated with the 2D model [10].

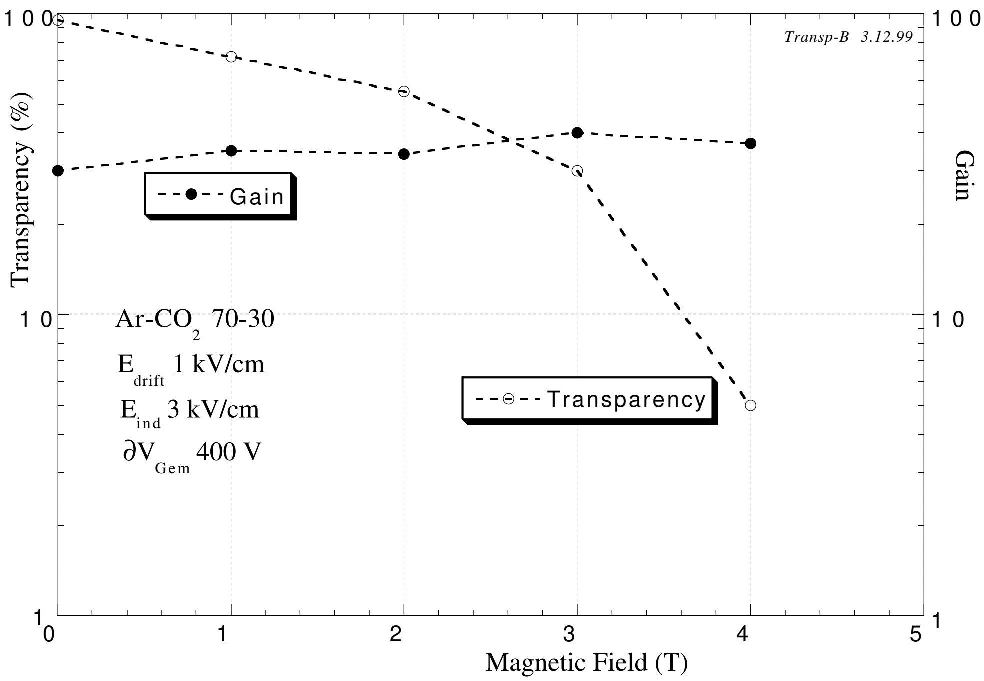

Fig. 17 The computed transparency and gain as a function of magnetic field (perpendicular to the electric field) with an Ar-CO_2 (70-30) gas mixture, and the electric field values as shown in the inset.

5. Conclusions

In this work, a 3-dimensional simulation of the operation of a Gas electron Multiplier has been performed describing the procedures in all detail. The results on transparency, positive ion feedback and operation in magnetic field have been corroborated by experiment to within experimental errors. Comprehensive procedures for performing the simulation have been appended.

References

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[15] T. Motos-Lopez and A. Sharma CERN Internal Report, CERN IT/99-05

Table 1

Material	**Relative Permittivity** ___	**Conductivity** **(μ)** **(siemens/meter)**
Al_2O_3_Ceramic	9.8	0
Aluminum Nitride	8.8	2.2e06
Alnico 5	1	2e06
Alnico 9	1	0
Beryllium Oxide	6.8	0.0001
Ceramic 5	1	0
FR4	4.4	6.3e05
Nd Fe 30	1	0
Teflon	2.2	0
Air	1.0006	0
Alumina	9.4	3.8e07
Aluminium	1	1e-09
Bakelite	4.8	0
Benzocyclobuten	2.6	0
Beryllium	1	1.5e07
Brass	1	1e07
Cast Iron	1	1.5e06
Chromium	1	7.6e06
Cobalt	1	1e07
Copper	1	5.8e07
Corning Glass	5.75	0
Cyanate Ester	3.8	0
Diamond	16.5	1e-13
Diamond Hi Pressure	5.7	0
Diamond CVD	3.5	0
Duroid	2.2	0
Epoxy-Kevlar	3.6	0
Ferrite	12	0.01
Gallium Arsenide	12.9	0
Glass	5.5	1e-12
Glass-PTFE	2.5	0
Gold	1	4.1e7
Graphite	1	7e04
Iron	1	1.03e07
Kapton	3.3-5.5	0
Lead	1	5e06
Marble	8.3	1e-08
Mica	6	1e-15
Mu-Metal	1	1.61e06
Nickel	1	1.45e07
Palladium	1	9.3e06
Perfect-Conductor	1	Infinity

Table 1 contd.

Platinum	1	9.3e06
Plexiglass	3.4	0.0051
Polyamide	4.3	0
Polyethylene	2.25	0
Polyamide-Quartz	4	0
Polystyrene	2.6	1e-16
Porcelain	5.7	1e-14
Quartz-Glass	3.78	0
Rubber-Hard	3	1e-15
Sapphire	10	0
Silicon	11.9	0
Silicon Dioxide	4	0
Silicon Nitrate	7	0
Silver	1	6.1e07
Soldeer	1	7e06
Stainless Steel	1	2e06
Tantalum	1	6.3e06
Teflon	2.8	0
Titanium	2.8	0
Tungsten	1	1.82e07
Vacuum	1	0
Water	81	0.0002
Zinc	1	4

Appendix I

```
# This script will create the geometry for the gem3D problem, with the
# basic cylindrical hole structure.
#
# First, let's declare the important variables.
# Note that all dimensions are in microns.
# THIS IS WHERE YOU SHOULD CHANGE THE NUMBERS !!

clearall
setunits "microns" "y"

assign side 140
assign int_diam 50
assign kapton_h 50
assign copper_h 5
assign up_size 250
assign down_size 250

# YOU SHOULD NOT NEED TO CHANGE ANYTHING BELOW THIS
# Let's do some calculations for the useful numbers...

assign xmax div side 2
assign xmin mul xmax -1                # Minimum x
assign ymax div side 2
assign ymin mul ymax -1                # Minimum y

assign int_rad div int_diam 2          # Compute internal radius

assign zmed div kapton_h 2             # The kapton is centered in z axis
assign n_zmed mul zmed -1              # the negative value
assign lower sub n_zmed copper_h       # the first copper below
assign zmin sub lower down_size        # and the minimum dimension now
assign upper add zmed  copper_h        # Now the symmetrical, up.
assign zmax add upper up_size

assign total_h add kapton_h (mul copper_h 2)   # kapton + 2 coppers

# STEP 0. Clear everything.

if GT getnumobjects 1
  delete "*"
end

# STEP 1.
#
# Let's draw the initial box that will be later divided into the copper and
# kapton.

box pos3 xmin ymin lower side side total_h  "brick"
Recolor "brick" 255 0 0

# STEP 2
#
```

```
# Now we are going to draw the hole in the brick.

cyl pos3 0 0 lower 2 int_rad total_h "hole"

# STEP 3
#
# Now this object is substracted from our initial brick.

subtract "brick" "hole"

# STEP 4
#
# Let's chop now the brick to create the upper and bottom copper.

origin pos3 0 0 n_zmed
split 2 2 "brick"
assign npiece getobjectname getnumobjects
rename npiece "down"

globalcs

origin pos3 0 0 zmed
split 2 2 "brick"
assign npiece getobjectname getnumobjects
rename npiece "kapton"

rename "brick" "up"

globalcs

recolor "up" 0 255 0
recolor "down" 0 255 0

# STEP 6. Finally, create the external boundary. In order to do this,two
# dummy objects will be created, above and below the main one. This can
# also help later with manual meshing.

box pos3 xmin ymin zmin side side down_size "dummy_down"
box pos3 xmin ymin upper side side up_size "dummy_up"

recolor "dummy_down" 0 128 128
recolor "dummy_up" 0 128 128
hide "dummy_down"
hide "dummy_up"

fitregion 0 "n"
recolor "background" 128 128 128
```

Appendix II

```
Global field True
Global drift True
Global trans True
Global gain True
Global esurf = 0
Global etran = 0
Global ekap  = 0
Global random True
Global mc False
&CELL
Global dir `~/Maxwell/3D/75mu.pjt`
Global bin `3D.bin`
Call inquire_file(bin,exist)
If exist Then
  read-field-map {bin}
Else
        field-map files "{dir}/v.reg" ...
        field-map files "{dir}/e.reg" ...
    field-map files "{dir}/d.reg" ...
            x-mirror-periodic y-mirror-periodic ...
             histogram-map
  save-field-map {bin}
Endif
&GAS
Ar-50-eth-50
If field Then
&FIELD
area -0.05 -0.05 0.05 0.05 view z=0
*pl vect
area -0.025 * -0.025 0.025 * 0.025 view y=0
*pl vect
*pl cont
area -0.020 -0.020 * 0.020 0.020 * view z=0.0050
grid 50
pl surf ez angles 60 120
Endif
If drift Then
&DRIFT
area -0.025 * -0.025 0.025 * 0.025 view x=0 rotate -90
track 0.0010 -0.025 0.020 0.0010 0.025 0.020 lines 50
int-par max-step 0.0001 int-acc 1e-11 nocheck-kink
dr tr
Endif
If trans Then
   &DRIFT
   int-par max-step 0.0005 int-acc 1e-11 noreject-kink m-c-dist-int 0.0002
   Global xmin=0
   Global xmax=sin(60*pi/180)*0.014
   Global ymin=-0.0070
   Global ymax=+0.0070
   Global z=0.0190
```

```
   Global n=25
*   area -0.025 -0.025 -0.0250 +0.0250 +0.0250 0.0250 view z={z}
   area -0.005 -0.02 -0.0250    +0.015 +0.02 0.0250 view z={z}
*   area view x+2*y+3*z=0 3d
*   tr -0.050 0.0 0.019 0.050 0 0.019 lines 50
*   dr tr
*   tr -0.050 0.007 0.019 0.050 0.007 0.019 lines 50
*   dr tr
   !rep function-1 polymarker-colour red marker-type circle marker-size 0.2
   !rep function-2 polymarker-colour blue  marker-type circle marker-size 0.2
   !rep function-3 polymarker-colour green   marker-type circle marker-size 0.2
   Call plot_drift_area
   For i From 1 Step 1 To n Do
      For j From 1 Step 1 To n Do
        If random Then
           Global x=xmin+(xmax-xmin)*rnd_uniform
           Global y=ymin+(ymax-ymin)*rnd_uniform
        Else
           Global x=xmin+(i-1)*(xmax-xmin)/(n-1)
           Global y=ymin+(j-1)*(ymax-ymin)/(n-1)
        Endif
        If mc Then
           Call drift_mc_electron(x,y,z,status)
        Else
           Call drift_electron_3(x,y,z,status)
        Endif
        Call plot_drift_line
        Call get_drift_line(xd,yd,zd,td)
        Call drift_information(`steps`,nd)
        If nd<1 Then Iterate
        Global zend=number(zd[nd])
        If zend>+0.0050 Then
          Say "Stopped, (x,y,z)=({x,y,z}), status={status}, zend={zend}"
           Call plot_marker(x,y,`function-1`)
           Global esurf=esurf+1
        Elseif zend<-0.0005 Then
*          Say "Through, (x,y,z)=({x,y,z}), status={status}, zend={zend}"
           Call plot_marker(x,y,`function-3`)
           Global etran=etran+1
        Else
*          Say "Kapton, (x,y,z)=({x,y,z}), status={status}, zend={zend}"
           Call plot_marker(x,y,`function-2`)
      Global ekap=ekap+1
        Endif
     Enddo
   Enddo
   Call plot_end
   Say "(esurf,ekap,etran)=({esurf,ekap,etran})"
Endif


&DRIFT
   area -0.025 -0.025 -0.0250    +0.025 +0.025 0.0250 view y=0 rot 180
   int-par max-step 0.0005 int-acc 1e-11 noreject-kink m-c-dist-int 0.0002
```

```
  Global plotdrift False
  If plotdrift Then
     Global opt `plot-electron,plot-ion`
  Else
     Global opt `noplot-electron,noplot-ion`
  Endif
  Call book_histogram(drift,100)
  Call book_histogram(top,100)
  Call book_histogram(kapton,100)
  Call book_histogram(down,100)
  Global tot=0
  Global niter 100
  For i From 1 To niter Do
     Say "Avalanche {i}/{niter}"
     If plotdrift Then Call plot_drift_area
     Call avalanche(0.001,0,0.020, opt, ne, ni, ...
        `t_ion, z_ion>0.0060`                ,drift, ...
        `t_ion, z_ion<0.0060&z_ion>0.0050` ,top, ...
        `t_ion, z_ion<0.0050&z_ion>0`       ,kapton, ...
        `t_ion, z_ion<0      &z_ion>-0.0010`,bottom, ...
        `t_ion, z_ion<-0.0010`               ,through)
     Global tot=tot+ni
     If plotdrift Then Call plot_end
  Enddo
  Call plot_histogram(drift,`Time [microsec]`,`Ions to drift region`)
  Call plot_end
  Call plot_histogram(top,`Time [microsec]`,`Ions to GEM top`)
  Call plot_end
  Call plot_histogram(kapton,`Time [microsec]`,`Ions to kapton`)
  Call plot_end
  Call plot_histogram(bottom,`Time [microsec]`,`Ions to GEM bottom`)
  Call plot_end
  Call plot_histogram(through,`Time [microsec]`,`Ions in collection`)
  Call plot_end
  Call inquire_histogram(drift, exists, set, channels, ...
     minimum, maximum, entries, average, sigma)
  Say "To drift region: {entries}/{tot}"
  Call inquire_histogram(top, exists, set, channels, ...
     minimum, maximum, entries, average, sigma)
  Say "To GEM top:      {entries}/{tot}"
  Call inquire_histogram(kapton, exists, set, channels, ...
     minimum, maximum, entries, average, sigma)
  Say "To kapton:       {entries}/{tot}"
  Call inquire_histogram(bottom, exists, set, channels, ...
     minimum, maximum, entries, average, sigma)
  Say "To GEM bottom:   {entries}/{tot}"
  Call inquire_histogram(through, exists, set, channels, ...
     minimum, maximum, entries, average, sigma)
  Say "To collection:   {entries}/{tot}"4
Endif
```