Depth of Interaction determination in GEM-based multilayer PET detectors

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Abstract
We present preliminary results obtained with a method permitting the determination of the conversion depth (DOI) in a position-sensitive, multi-layer γ ray or neutron detector making use of a stack of Gas Electron Multipliers and converter foils.

Keywords: Gas Electron Multiplier; neutron and gamma detection; depth of interaction

Owing to their excellent position resolution and high rate capability, Gas Electron Multiplier (GEM) detectors are widely used for the tracking of charged particles in high-energy physics [1]. With appropriate deposits on the electrodes or additional converter sheets, the device is used for detection and localization of neutrons [2] and high-energy X-rays [3,4]. To compensate for the low efficiency of a single element, multi-layer structures can be made, with stacks of several converter-GEM pairs; ionization released by a neutron or photon conversion anywhere in the stack is transported through the structure to an end-cap position-sensitive GEM multiplier. Detailed simulation studies have been made to compute efficiencies and optimize the geometry of such structures, aiming at applications for portal imaging and PET cameras [5,6], and promising results have been reported [7].

A problem hinders however the use of the device. In a multi-layer GEM-converted stack, one has to ensure that the amount of charge transported to the end-cap does not depend on the conversion depth. This implies that each cell must have an effective gain close to unity; the terminal multiplier brings then the charge to the level needed for detection and localization. While it is easy to have unitary gain cells by applying appropriate voltages, the thickness of each layer, typically several mm, adds an (unknown) delay to the final charge collection, implying a poor time resolution. For ten layers, and using a fast gas, this delay is of several hundred ns, seriously

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restricting the use of the technology. Moreover, for thick detectors and off-normal angles of incidence of radiation, a large parallax error adds an error to the coordinate determination.

This note describes preliminary results obtained with a structure that overcomes the described drawback. The basic concept is to design each element in a multi-cell GEM-converter stack with high gain, to allow local detection of the event, but very low charge transmission to the following element. If G is the effective gain of a foil, the goal of unitary gain for each layer is achieved if its transmission is 1/G. In the present note, we demonstrate that this can be achieved using high gain GEMs coupled to a converter foil of low transparency, and optimized values of electric fields.

For the measurements, we have built a detector using standard GEM foils, each having 70 μm holes at 140 μm pitch, and an active area of 10x10 cm^2. As a converter mesh, we used a 10 μm thick copper foil, chemically pierced with 50 μm diameter holes at 400 μm pitch[1]. The low optical transparency (~3%) helps reduce the electron transparency, and results in an almost full use of the conversion surface. Although for a real device the thickness of the converter may have to be increased, the optical transparency can be made equivalent. The detector (Fig. 1) has two identical cells with alternating low (E_L) and high fields (E_H) above and below each GEM. Ionization produced in the upper layer is multiplied in GEM1 and transported to the mesh. Owing to its low transparency, the mesh collects most of the amplified charge, with only a small, field-dependent fraction transmitted to the second cell. The last electrode collects the final electron charge. All gaps between foils are 2 mm wide. Equal-gain charge amplifiers connected to the converter foil and to the anode, followed by analogue-to-digital converters, permit recording the direct and transmitted charges. For the present tests, only the total charge was recorded, but a suitable segmentation of the end-cap electrode would allow localizing the events with sub-mm accuracy [8]. The potentials for operation are applied using independent HV power supplies through a protection resistor. For the fill gas we used an open-flow Ar-CO_2 mixture in the proportion 70%-30%.

The electron transparency of the mesh has been measured separately in a simpler setup, consisting of two gas layers separated by planar electrodes, with the

[1] Provided by Rui De Oliveira (CERN-TS-DEM)

mesh in the middle. Ionization currents, produced by an X-ray beam that interacts in one of the gaps, are recorded on all electrodes as a function of fields above and below the mesh. The transparency is deduced from the ratio of currents [9]. Fig. 2 shows the measured electron transparency as a function of the field ratio E_H/E_L, for two choices of the sum of the fields. For high values of the ratio, a transparency around 0.3% is achieved. Note that the transparency depends slightly on the field strengths, and not only on their ratio: this is a probable consequence of different electron diffusion in the gas.

Exposing the detector shown in Fig. 1 to a collimated 8.9 keV X-ray beam, we could inject a known amount of charge into the first cell. The effective gain of each GEM, defined as ratio of the charge collected on the mesh (or anode) and the charge injected into the foil, was calibrated using standard procedures [10]. The calibration takes into account that the effective gain depends on the field E_H below the GEM electrode (called induction field in previous work [11]). To emulate a multiple device, identical voltage differences are applied to both cells. We recorded the charge on the mesh and on the anode as a function of GEM voltages and electric fields above and below the mesh (E_H and E_L respectively). A summary of the results is shown in Fig. 3, giving the ratio of mesh and anode charge as a function of GEM effective gain, for two choices of fields. Owing to the different charge collection efficiency, the unitary ratio is reached at different gains; as expected, the GEM gain at unit ratio corresponds rather well to the inverse of the measured electron transparency for the same fields (see Fig. 2). The rightmost data, obtained with a low value of E_L, allow a higher GEM gain, with however the drawbacks of a very low electron drift velocity in the gas mixture used. For the other set of data, the low field is higher, and so is the drift velocity, but the GEM gain at unitary ratio is lower. In future work, this can be improved using a gas in which the drift velocity is high at low fields, such as mixtures of argon with methane or CF_4. Fig. 4 shows an example of pulse height spectra recorded with 8.9 keV X-rays on the mesh (top histogram, shifted upwards) and on the anode (lower histogram) for the condition of a unitary gain ratio. Because of the noise contribution at moderate gains, the energy resolution is modest, but only slightly degraded by the low charge transmission through the mesh.

In conclusion, we have demonstrated that the proper choice of geometry and field conditions permit operation of a GEM-converter pair at a large enough gain to allow direct detection of gamma ray conversions in a layer, with a transmitted gain close to unity in each cell. In a multi-layer stack, detection of a pulse on one of the meshes will indicate the depth of interaction, while positional information is obtained from an end-cap multiplier using standard readout methods with projective strips or pads. Measurements with standard GEM detectors suggest that a time resolution around 10 ns could be achieved using standard gas mixtures [12]. This can be improved using faster, CF_4-based mixtures [13]. Multiple conversions in the same stack can be identified if occurring at different depths by the time information.

Once optimized, the voltage distribution can be provided with a resistor chain and a single power supply, as in existing setups. To avoid the need of reaching excessive voltages, the total number of elements in the stack may have to be limited. Moreover, a decrease in thickness of the high field gap between GEM and converter, and an increase of the low-field transfer gap help in reducing the overall operating voltage, and to increase the ionization yield from conversion electrons. As an example, a GEM-converter cell with 1 and 3 mm gaps requires an overall voltage difference of around 500 V to operate. A ten-cell stack then requires a reasonable value of about 5 kV. A further reduction could be obtained with a different choice of the filling gas. According to the quoted simulations, and using lead as converter, this would provide a detection efficiency of 5% for 511 keV gamma rays [5]. Several independent stacks can then be assembled together to reach useful values of efficiency, a solution permitted by the low cost of GEM-based single detectors.

FIGURE CAPTIONS

Fig. 1: Schematics of the test detector with two identical cells.

Fig. 2: Direct measurement of the electron transparency of the mesh used in the setup, as a function of fields.

Fig. 3: Pulse height ratio between anode and mesh signals as a function of GEM effective gain as seen on the mesh, for two choices of fields.

Fig. 4: Pulse height spectra for 8.9 keV X-rays recorded on the mesh and on the anode in the condition of unitary gain ratio.

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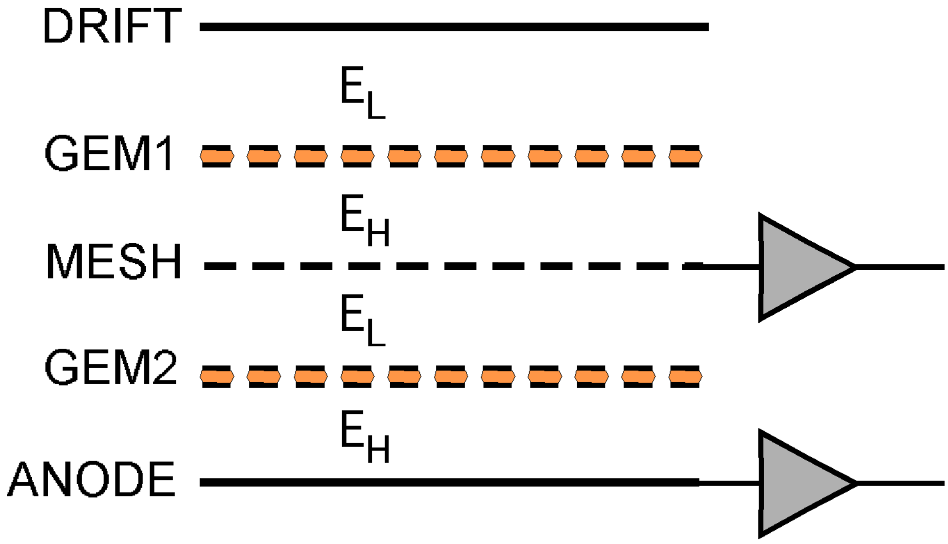

DRIFT
E_L
GEM1
E_H
MESH
E_L
GEM2
E_H
ANODE

Fig. 1

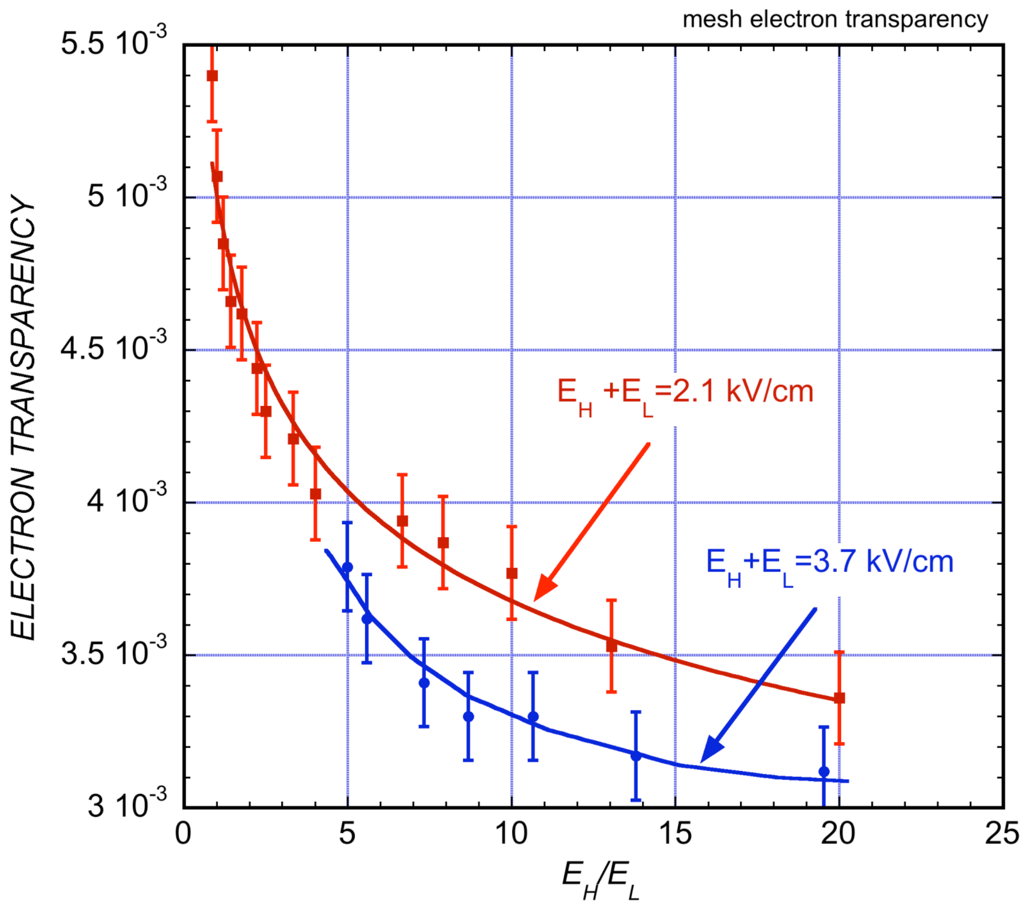
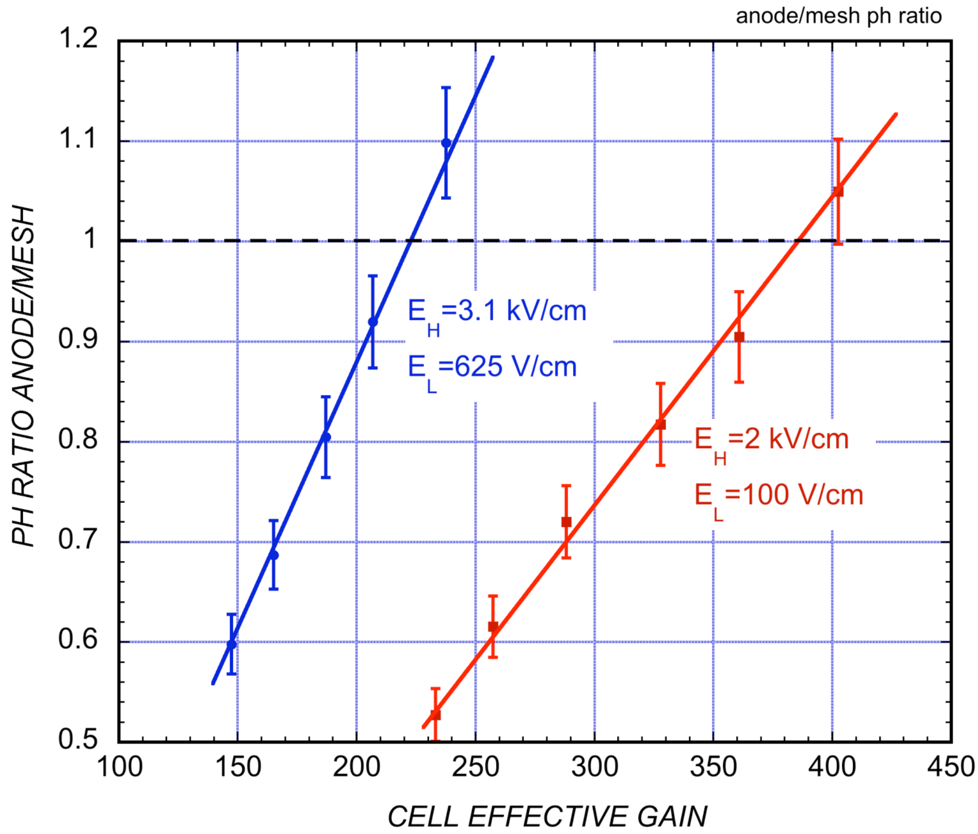
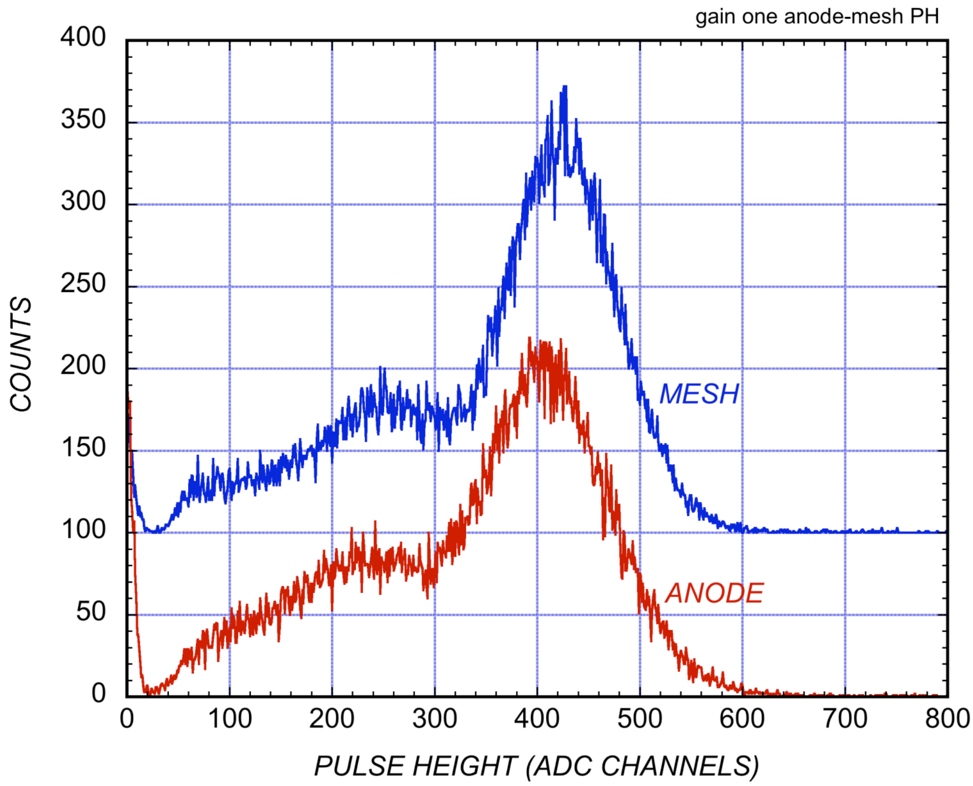

mesh electron transparency
5.5 10^-3
5 10^-3
4.5 10^-3
4 10^-3
3.5 10^-3
3 10^-3
0
5
10
15
20
25
ELECTRON TRANSPARENCY
E_H/E_L
$E_H + E_L$=2.1 kV/cm
E_H+E_L=3.7 kV/cm

Fig. 2



anode/mesh ph ratio
PH RATIO ANODE/MESH
CELL EFFECTIVE GAIN
E_H=3.1 kV/cm
E_L=625 V/cm
E_H=2 kV/cm
E_L=100 V/cm

Fig. 3



gain one anode-mesh PH
COUNTS
PULSE HEIGHT (ADC CHANNELS)
MESH
ANODE

Fig. 4