Lab Book - Helmholtz Detector Workshop 2025

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1 Introduction

This is the lab book for the Helmholtz Detector school 2025 at the FTD, Bonn. It concentrates on Micropattern Gaseous Detectors (MPGD) and discusses the detector design, construction and performance at the example of a GEM-based detector. The sessions are based on the RD51 school in 2023 and DRD1 school in 2024. Also, the text is partially taken from these lab books.

2 First Session - Construction of triple-GEM Detector in the Clean Room

This session starts with an introduction to the code of conduct in the clean room. The most important aspect is the dressing starting with the blue overshoes in the anteroom. Students will then enter the changing room to put on the hairnet, beard cover, clean room coat and white overshoes and also take gloves. Objects that will be used in the clean room have to be cleaned before bringing them in (also mobile phones).

In this session the different steps of producing a triple-GEM detector are demonstrated, discussed and performed.

2.1 GEM-Production

GEMs are the essential parts of many modern gaseous detectors as they are used as the gas amplification stage. They consist of a 50 µm thick kapton/apical foil covered on both sides with 5 µm copper. To improve the adhesion of copper to apical a very thin chromium layer is placed between the two materials. Holes are etched into this sandwich structure in a hexagonal pattern as shown in the SEM picture of a GEM in Figure 1. The holes have an inner diameter of 50 µm, an outer diameter of 70 µm and a pitch of 140 µm. If different electrical potentials are applied to the copper electrodes, electrical dipole fields are formed in the holes. If an electron arrives in the hole it undergoes gas amplification nd a large number of electrons is released in the volume below, while most ions are neutralized at the top electrode and only few ions are released i nthe gas volume above (see Figure 2).

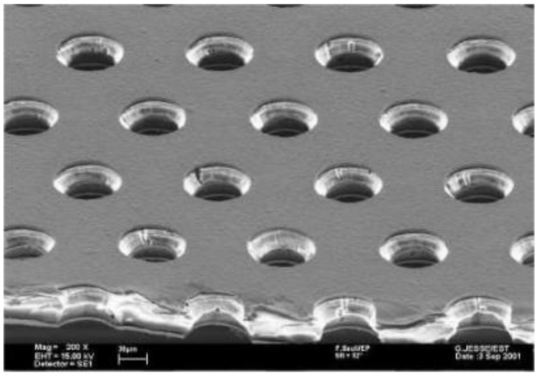


Figure 1: SEM picture of a GEM (Courtesy of CERN).

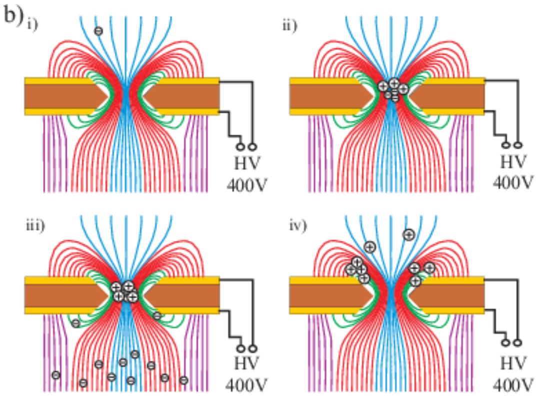


Figure 2: Symbolic process of gas amplification in a GEM.

The production of GEMs is delicate and requires a clean environment since small dust particles can produce either holes at unwanted places, closed holes or distortion of the correct edge shape. The process had been developed by Rui de Oliveira at CERN, but has been copied by several institutes and companies. In a first part of this session the production of GEMs will be shown in parts, were several steps will be performed life in the clean room. For this, prefabricated samples of GEMs will be etched in the wet bench of ISO7. These steps will include the first copper etching and the following chromium etching. The remaining steps will be explained.

2.2 Quality Assurance - QA

For large scale experiments such as CMS, a reliable and continuous operation with little change and very little degradation of the performance are essential requirements for the detectors. To fulfill these requirements, intensive tests before the final design choices are required. But since small variations in the production process or contaminations may lead to performance losses during operation, also a tight quality control is necessary during the mass production. To ensure, that only GEM-foils of sufficient quality will be installed, all GEMs have to be checked before the assembly in the detector. Both electrodes of each GEM are connected to HV and the HV is applied directly. During this process the leakage current is observed. Sparks might occur a few times at the beginning of a new voltage step, but should cease soon and leakage currents should drop to a nanoamp level. If the GEM is stable for a several minutes, a next voltage level is tested until the maximum level (typically 500 V in air) is reached. If the final level is sucessfully passed, the GEM is accepted for further use.

The quality assurance will take place in an ISO6 room. For this an extra level of cleanliness is necessary and the personnel has to dress in whole-body suits in a second cleanroom lock.

2.3 Detector

Students will construct a triple GEM detector similar to the one used in the second session (see Section 3). The different parts can be seen in the exploded view in Figure 3. The detector consists of a readout board, which features one large pad for convenience. A triple GEM structure will be mounted on the four screws and a cathode to define the drift region. They are encased by the detector body, which is sealed by an o-ring and 12 screws. The layout of the detector and the choice of materials will be discussed. In addition the HV distribution of the detector will be scrutinized. The HV is distributed by a resistor voltage divider. A schematic is shown in Figure 4. The correct SMD resistors as well as the connectors will be soldered during the session to the readout board. The detector will be completely assembled and closed.

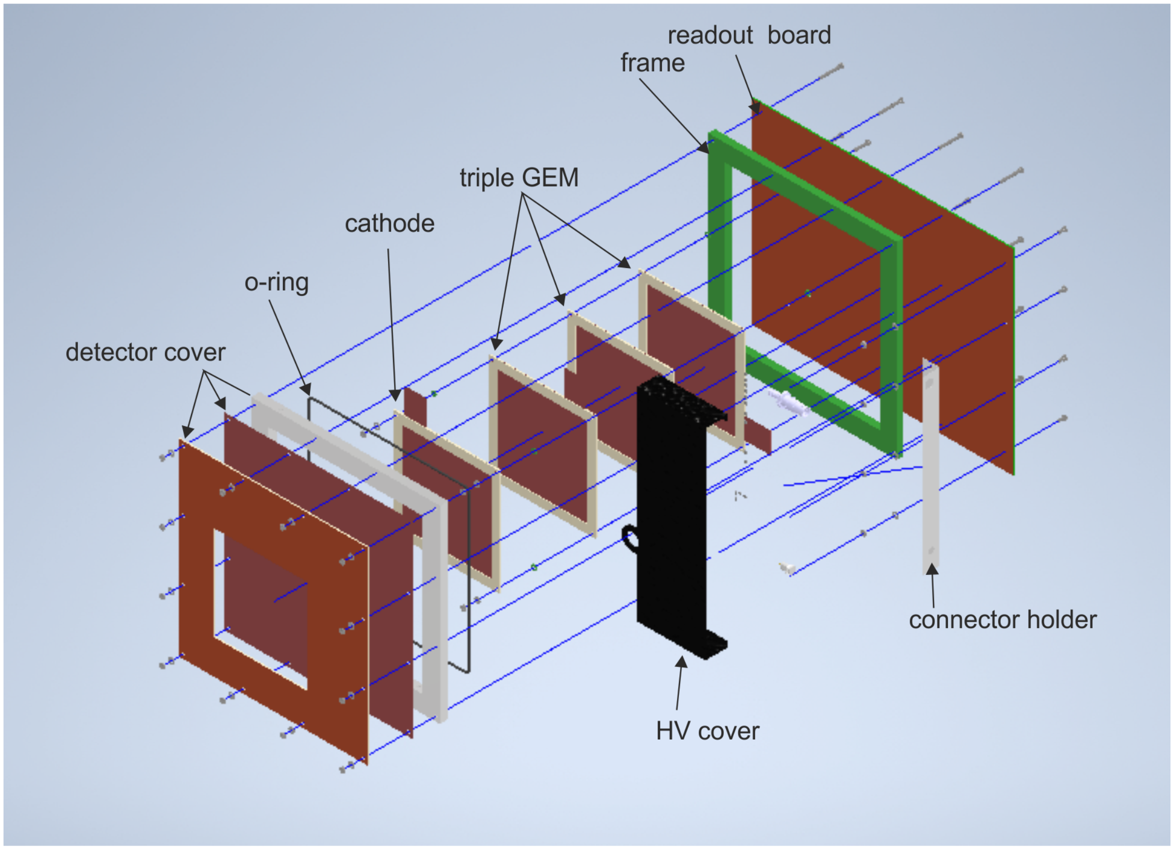


Figure 3: Exploded view of triple-GEM detector.

2.4 Check Gas Tightness

Depending on the length of the drift distance, the operation gas pressure and the expected rate of particles the gas has to be very clean and the detector has to be very gas tight. Also this aspect of the detector has to be tested after production. Depending on the detector design, different techniques of verifying the detector can be applied. A setup has been installed in an experimental lab and the detectors built in the cleanroom will be tested.

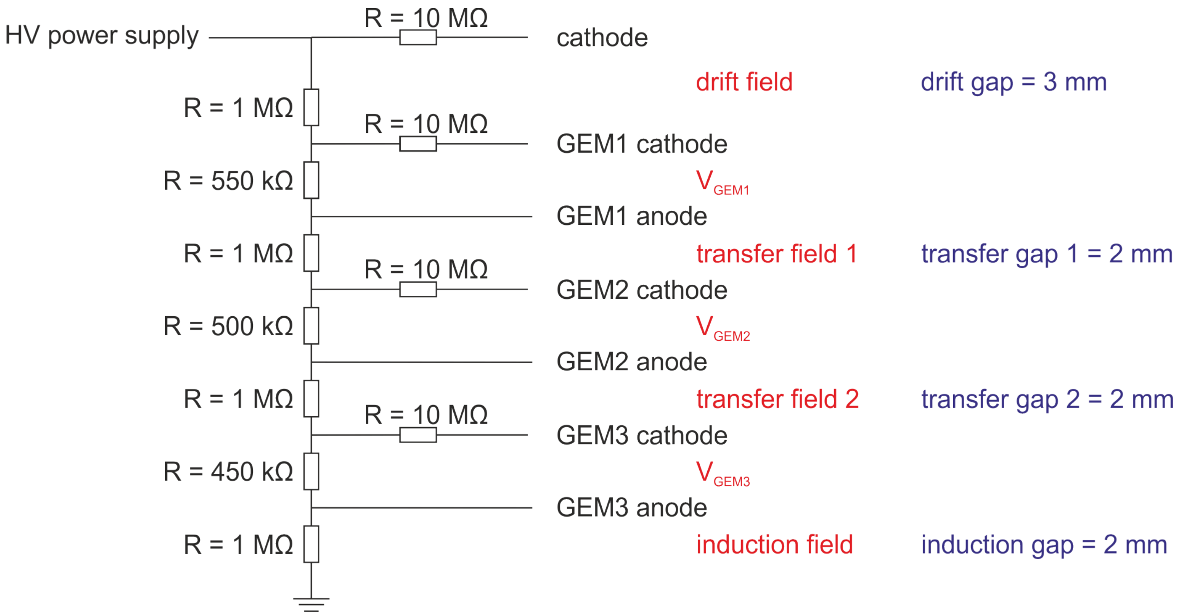


Figure 4: Resistive Divider Chain.

Tasks

1. Participate in the production of the GEMs.
2. Check the HV resistivity of one GEM and decide if the Quality of the GEM is good enough.
3. Construct a complete triple-GEM detector. In this part the important design choices are discussed like materials and layout. A particular attention is given to gas purity. Students will install the resistor divider chain, assemble the connectors, GEMs, cathode and close the detector.
4. As a final step, the gas tightness of the detector will be tested in an experimental lab. Different types of leak test will be performed.

3 Second Session - Measuring with a GEM Detector

3.1 Introduction

In this session, we want to experimentally determine the gain of a GEM-based gaseous detector. We define the gain G_{eff} as the ratio of the current on the readout electrode I_{readout} and the ionisation current $I_{\text{ionisation}}$ (created in the drift volume of the detector)

$$G_{\text{eff}} = \frac{I_{\text{readout}}}{I_{\text{ionisation}}} \tag{1}$$

The triple GEM detector that you have (or will) set up in the cleanroom has a similar configuration as the detectors that are built for the AMBER experiment (former: COMPASS) at CERN [A+02]. They consist of three standard GEM foils and make use of a passive voltage divider (PVD) to power the individual electrodes as depicted in fig. 5. With the PVD, you only need one high voltage input which gets cascaded down by a resistor chain. The resistors are fixed to 550 kΩ for GEM1, 500 kΩ for GEM2, 450 kΩ for GEM3 and 1 MΩ for the drift field and all transfer fields. Note that the gap sizes (distances between the individual electrodes) are always 2 mm, except for the distance between drift and GEM1 which is 3 mm. With these information, you can calculate the voltage across each GEM and the strength of the electric fields in between the GEMs.

In order to be fully efficient, these detectors typically run at a gain of ≈ 8000. Therefore, we need to find the input voltage that is required to reach a gain of 8000.

For this, we are conducting a few measurements with a radioactive ^{55}Fe source. ^{55}Fe decays via electron capture to an excited state of ^{55}Mn and in the relaxation process, $K\alpha$ and $K\beta$ X-ray photons are emitted, which have an energy of 5.9 keV and 6.5 keV, respectively. The $K\alpha$ transition is 8.8 times more likely to occur than the $K\beta$ transition [Bea67]. These X-ray photons interact in the drift volume of our detector and create electron-ion pairs. The electrons then drift towards the first GEM where gas amplification occurs. This process repeats until the last GEM is reached and the signal is induced on the readout plane. Sometimes, however, if the incoming photon ejects an electron from the K-shell of argon, the hole gets filled by e.g. an electron from the L-shell and a photon is created which can potentially leave the detector. In this case, we only measure a fraction of the signal. An example spectrum of the expected signal is depicted in fig. 6.

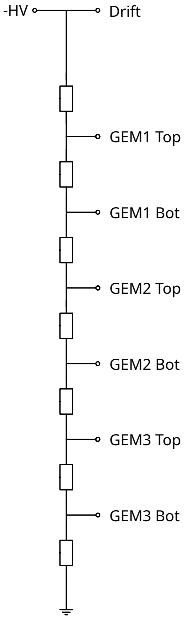


Figure 5: The passive voltage divider (PVD).

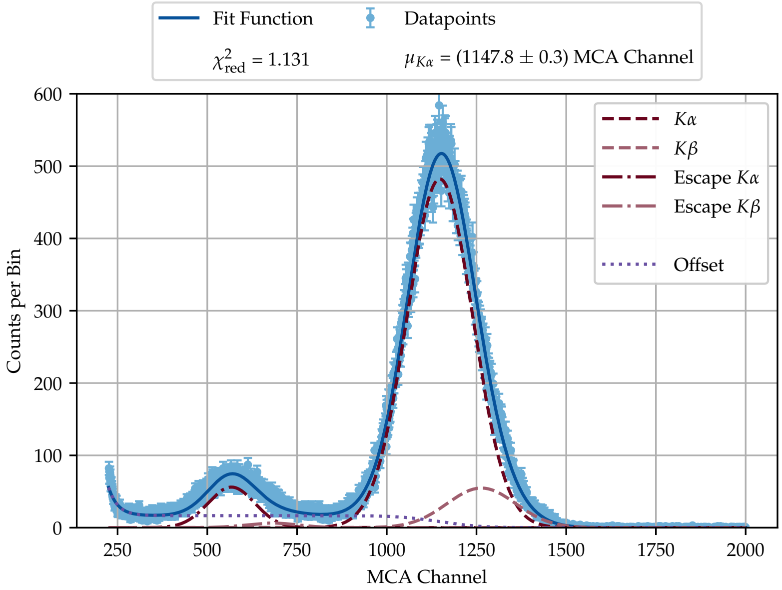
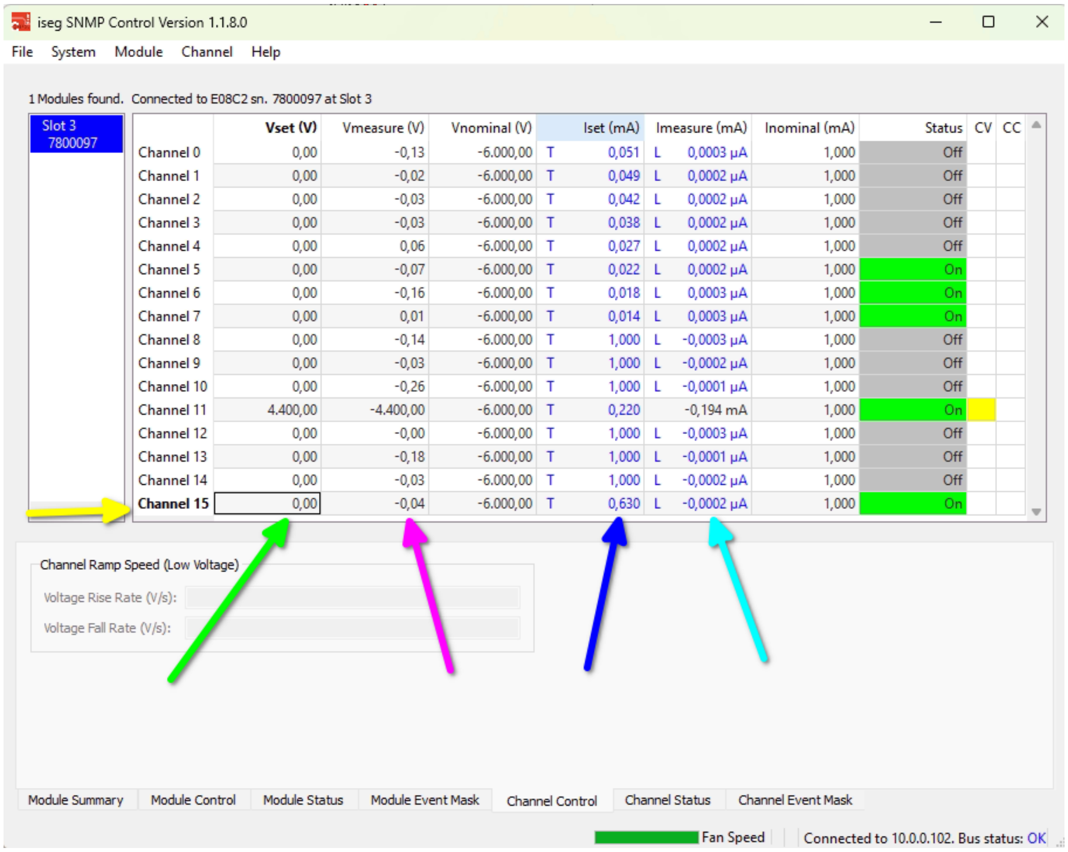


Figure 6: Example spectrum of a ^{55}Fe source measured with a GEM-based gaseous detector. The gas composition was Ar/CO$_2$ (90/10).



1 Modules found. Connected to E08C2 sn. 7800097 at Slot 3

	Vset (V)	Vmeasure (V)	Vnominal (V)		Iset (mA)		Imeasure (mA)	Inominal (mA)	Status	CV	CC
Channel 0	0,00	-0,13	-6.000,00	T	0,051	L	0,0003 µA	1,000	Off		
Channel 1	0,00	-0,02	-6.000,00	T	0,049	L	0,0002 µA	1,000	Off		
Channel 2	0,00	-0,03	-6.000,00	T	0,042	L	0,0002 µA	1,000	Off		
Channel 3	0,00	-0,03	-6.000,00	T	0,038	L	0,0002 µA	1,000	Off		
Channel 4	0,00	0,06	-6.000,00	T	0,027	L	0,0002 µA	1,000	Off		
Channel 5	0,00	-0,07	-6.000,00	T	0,022	L	0,0002 µA	1,000	On		
Channel 6	0,00	-0,16	-6.000,00	T	0,018	L	0,0003 µA	1,000	On		
Channel 7	0,00	0,01	-6.000,00	T	0,014	L	0,0003 µA	1,000	On		
Channel 8	0,00	-0,14	-6.000,00	T	1,000	L	-0,0003 µA	1,000	Off		
Channel 9	0,00	-0,03	-6.000,00	T	1,000	L	-0,0002 µA	1,000	Off		
Channel 10	0,00	-0,26	-6.000,00	T	1,000	L	-0,0001 µA	1,000	Off		
Channel 11	4.400,00	-4.400,00	-6.000,00	T	0,220		-0,194 mA	1,000	On	🟨	
Channel 12	0,00	-0,00	-6.000,00	T	1,000	L	-0,0003 µA	1,000	Off		
Channel 13	0,00	-0,18	-6.000,00	T	1,000	L	-0,0001 µA	1,000	Off		
Channel 14	0,00	-0,03	-6.000,00	T	1,000	L	-0,0002 µA	1,000	Off		
Channel 15	0,00	-0,04	-6.000,00	T	0,630	L	-0,0002 µA	1,000	On		

Connected to 10.0.0.102. Bus status: OK

Figure 7: Screenshot of the software used to control the high voltage.
Yellow arrow: We are using channel 15 only.
Green arrow: Here, you can set the voltage for channel 15.
Pink arrow: The voltage measured by the power supply.
Blue arrow: The trip current for the channel. You have to set it before ramping the voltage!
Light blue arrow: The current read by the power supply. Always check it for consistency.

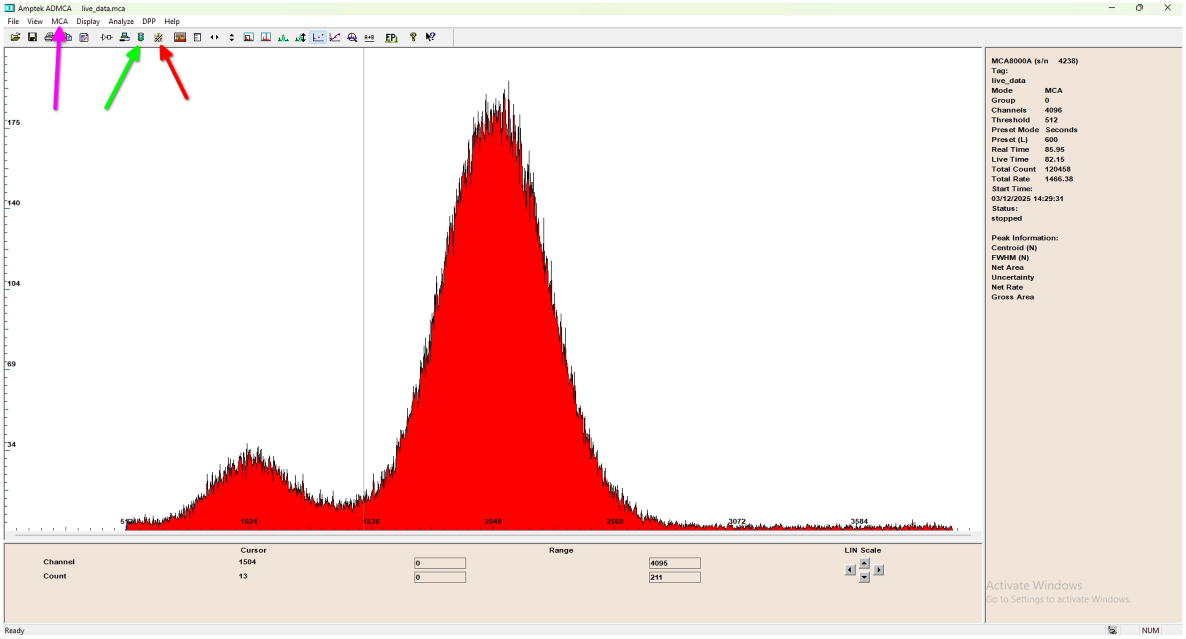
3.2 Operating the Detector

First, you have to connect the high voltage power supply to the detector. If someone already connected the cables, double check if everything is properly connected. The application of the high voltage is a very crucial step as mistakes often lead to a severe damage of the detector. If you are sure that the cables are all properly connected, you can start to slowly ramp up the voltage. The working point of the detector will be somewhere between 3000 V to 3600 V.

For ramping the voltage, we are using the program “iseg SNMP Control”. You can see a screenshot of it in fig. 7. Before you ramp up the detector to the mentioned values, we highly recommend that you start slowly. Apply an intermediate voltage of e.g. 100 V and calculate the expected current that the high voltage power supply has to deliver (i.e. take into account the total resistance of the PVD). If you now apply this voltage and you significantly exceed this current, you have a strong indicator that something is not working properly. Now you can prepare the ramp-up of the detector to a higher voltage. Again, we recommend that you go in intermediate steps (e.g. 1000 V, 2000 V, 2500 V, 3000 V) and before (!) you ramp, calculate the expected current and set a reasonable trip current. The trip current must never be exceeded, otherwise, the detector will ramp down. At 3000 V, you can take a look of the signals on an oscilloscope.

3.3 Analysing the Signals

Now that your detector is at a reasonable voltage, it is time to analyse the signals. For this, we first use an oscilloscope. In order to do this, we connect the readout plane to a pre-amplifier. The output



MCA8000A (s/n 4238)
Tag:
live_data
Mode MCA
Group 0
Channels 4096
Threshold 512
Preset Mode Seconds
Preset (L) 600
Real Time 85.95
Live Time 82.15
Total Count 120458
Total Rate 1466.38
Start Time:
03/12/2025 14:29:31
Status:
stopped

Peak Information:
Centroid (N)
FWHM (N)
Net Area
Uncertainty
Net Rate
Gross Area

Channel 1504 0 4095
Count 13 0 211

Figure 8: Screenshot of the software used to measure pulse height spectra.
Green arrow: Start and stop the measurement.
Red arrow: Delete data (should always be done before a new measurement is started).
Pink arrow: Under “Acquisition Setup”, you can set things like the threshold.

of the pre-amplifier is fed into a shaping amplifier where you can set the electric gain. The output of the shaping amplifier can then be viewed on the scope.

Without a radioactive source, you mainly see the noise of the baseline. You can try to minimise the noise if you want to. Your tutor can then bring the radioactive source. If the gain of your detector is strong enough, you should see the first peaks which are higher than the baseline fluctuations. You can ramp up the detector a bit more (e.g. in steps of 50 V to 100 V) to see if the signal amplitude is rising.

If you have a decent signal-to-noise ratio, you can connect a multi channel analyser (MCA) instead of the oscilloscope. The MCA is connected to the computer and can be controlled with the software “ADMCA”. A screenshot of this software is depicted in fig. 8. Now you can again ramp up the detector voltage until you have a clear spectrum, similar to the one depicted in figs. 6 and 8. Maybe you have to tweak the electric gain of the shaping amplifier and the threshold in the MCA software a bit.

3.4 Calculating the Gain

From the spectrum alone, we can not calculate the effective gain. But we can calculate the ionisation current from this spectrum which is one of the two quantities that we need to calculate the effective gain according to eq. (1). For this, we first need to find the integral A of each peak. This number is the number of photons that interacted in our detector (think about this statement, it is not trivial). Next, you multiply this number by the average energy E_{avg} of the photons responsible for this peak. Sum up the contributions of the individual peaks and in a last step, we need to divide this value by the time t_{meas} it took to take the spectrum and the mean energy required to create an electron-ion pair W_{ion} which is 26.7 eV for the used gas mixture.

$$I_{\text{ionisation}} = \frac{A \cdot E_{\text{avg}} \cdot e}{t_{\text{meas}} \cdot w_{\text{ion}}} \tag{2}$$

In order to measure the current on the readout electrode, we can simply connect it to a precise ammeter. Typically, the expected currents are in the order of pA to nA, depending of course on the gain of the detector and the strength of the signal. Now you can tune the detector voltage until you measure a gain of ≈ 8000.

Tasks

1. At which voltage is the gain of the detector 8000?
2. What is the dependency of the gain on the applied voltage?
3. If you already simulated the gain of a GEM, how do your results compare to the measurements? For this, you have to calculate the individual GEM voltages (use the values of the PVD) and compare to your simulation.

   If you did not do the session about simulation, yet, write down your findings and compare them later.
4. With this measurement method, the measurement uncertainties are rather big. In addition, external parameters like temperature and pressure variations also affect the gain. Is the exact gain important for the operation of a gaseous detector in an experiment?
5. With this method, we can only measure the gain of the whole detector. What do we have to change in order to measure a spatially resolved gain map? Why could this be important for the operation in an experiment?

3.5 Measurement with a Hybrid Detector

In order to determine the gain of a single GEM at low voltages, we also set up a different detector. It consists of a drift foil, a GEM foil as a first and a MicroMegas [GRRC96] as a second amplification stage[1]. With this setup, we can create a "double spectrum" as depicted in fig. 9 (left side).

The part of the spectrum at high MCA channels (yellow) originates from photons, that interacted between drift foil and GEM foil. The liberated electrons are then amplified by both GEM and MicroMegas. The other part of the spectrum (dark red) originates from interaction of photons between GEM foil and MicroMegas. Consequently, the liberated electrons are only amplified by the MicroMegas. This is shown schematically in fig. 9 (right side).

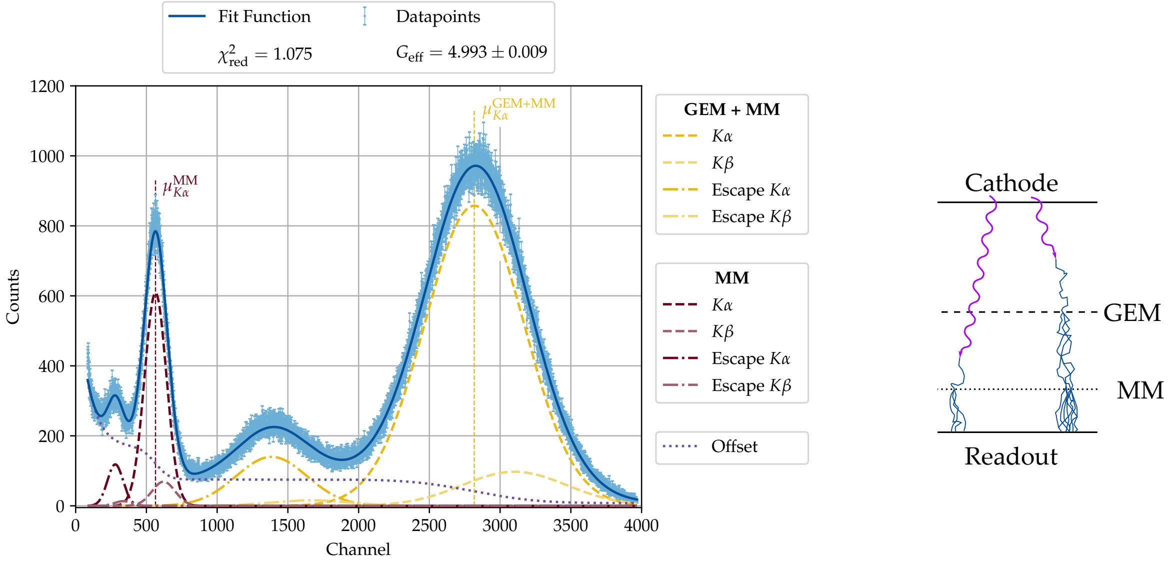


Figure 9: Left: A double spectrum recorded with a hybrid detector (GEM and MicroMegas).
Right: Schematic of the interaction of photons in a hybrid detector.

From this spectrum, you can directly calculate the effective gain G_{eff} by dividing the peak position of the GEM and MicroMegas peak $\mu_{K\alpha}^{\mathrm{GEM+MM}}$ by the peak position of the GEM-only peak $\mu_{K\alpha}^{\mathrm{MM}}$.

$$G_{\mathrm{eff}} = \frac{\mu_{K\alpha}^{\mathrm{GEM+MM}}}{\mu_{K\alpha}^{\mathrm{MM}}} \tag{3}$$

In order to operate the detector, we use a different powering scheme – the separate channel power supply. For this, we first connect each channel to a resistor to ground with a resistance of 100 MΩ. With this, we establish a current to ground which helps to sink the currents created in the detector. The main advantage of this setup is that we can set the voltage of each individual channel. We use a self-developed slow control to set the voltages. A screenshot of it is depicted in fig. 10 and you find a bit of explanation in the caption.

Before you can observe a signal, you should first ramp up the detector to a reasonable voltage. Similar to the procedure described in section 3.2, you should be very careful when ramping up the detector. Think about the current that you expect and set a trip limit before you start ramping. We recommend to start with a GEM voltage of 250 V and a MicroMegas voltage of 450 V.

For the analysis of the signal, the procedure is similar to the one described in section 3.3. We also use a pre-amplifier and a shaping amplifier. First, one should use an oscilloscope to get familiar with the baseline and its noise. Try to minimise the noise. When the detector is at a reasonable voltage, you can ask your tutor to place the radioactive source on the detector. If you do not see a signal, increase the MicroMegas voltage a bit (as all signals get amplified by the MicroMegas). Do not exceed 500 V across the MicroMegas.

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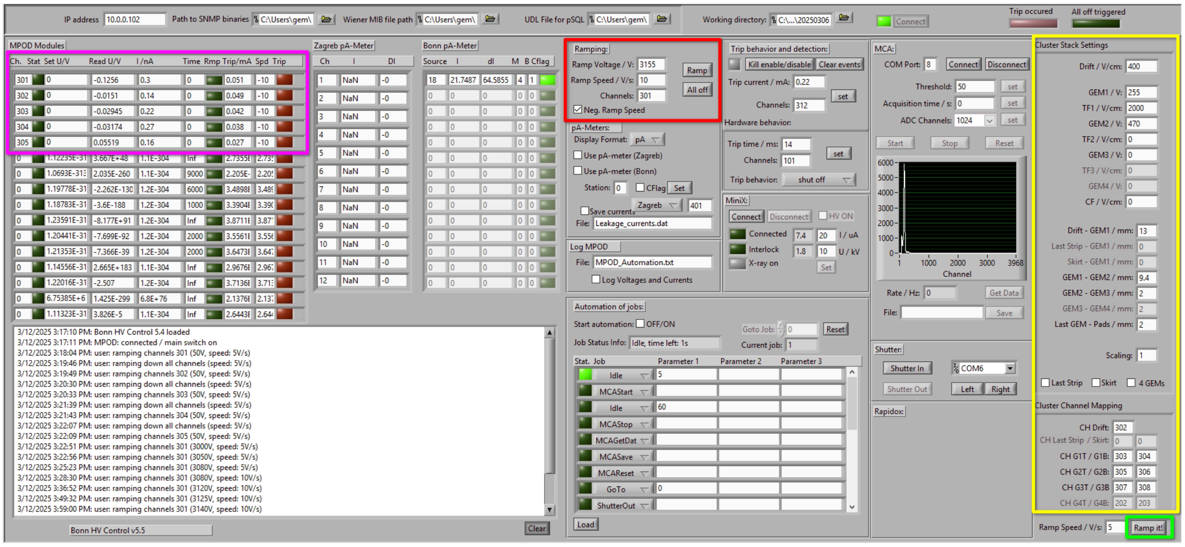
[1] A MicroMegas is a thin mesh, which is located 128 µm above the readout. Between mesh and readout, gas amplification occurs.


IP address: 10.0.0.102
Path to SNMP binaries: C:\Users\gem\
UDL File for pSQL: C:\Users\gem\

MPOD Modules

Ch.	Stat	Set U/V	Read U/V	I /nA	Time	Rmp	Trip/mA	Spd	Trip
301	●	0	-0.1256	0.3	0	●	0.051	-10	●
302	●	0	-0.0151	0.14	0	●	0.049	-10	●
303	●	0	-0.02945	0.22	0	●	0.042	-10	●
304	●	0	-0.03174	0.27	0	●	0.038	-10	●
305	●	0	0.05519	0.16	0	●	0.027	-10	●
0	●	1.12235E-31	3.667E+48	1.1E-304	Inf	●	2.7355E	2.73	●
0	●	1.0693E-313	2.035E-260	1.1E-304	9000	●	2.205E-	2.20	●
0	●	1.19778E-31	-2.262E-130	1.2E-304	6000	●	3.4898E	3.48	●
0	●	1.18783E-31	-3.6E-188	1.2E-304	1000	●	3.3904E	3.39	●
0	●	1.23591E-31	-8.177E+91	1.2E-304	Inf	●	3.8711E	3.87	●
0	●	1.20441E-31	-7.699E-92	1.2E-304	2000	●	3.5561E	3.55	●
0	●	1.21353E-31	-7.366E-39	1.2E-304	2000	●	3.6473E	3.64	●
0	●	1.14556E-31	2.665E+183	1.1E-304	Inf	●	2.9676E	2.96	●
0	●	1.22016E-31	-2.507	1.2E-304	Inf	●	3.7136E	3.71	●
0	●	6.75385E+6	1.425E-299	6.8E+76	Inf	●	2.1376E	2.13	●
0	●	1.11323E-31	3.826E-5	1.1E-304	Inf	●	2.6443E	2.64	●

Ramping:
Ramp Voltage / V: 3155
Ramp Speed / V/s: 10
Channels: 301
☑ Neg. Ramp Speed

pA-Meters:
Display Format: pA
☐ Use pA-meter (Zagreb)
☐ Use pA-meter (Bonn)
Station: 0 ☐ CFlag
☐ Save currents Zagreb 401
File: Leakage_currents.dat

Cluster Stack Settings
Drift / V/cm: 400
GEM1 / V: 255
TF1 / V/cm: 2000
GEM2 / V: 470
TF2 / V/cm: 0
GEM3 / V: 0
TF3 / V/cm: 0
GEM4 / V: 0
CF / V/cm: 0
Drift - GEM1 / mm: 13
Last Strip - GEM1 / mm: 0
Skirt - GEM1 / mm: 0
GEM1 - GEM2 / mm: 9.4
GEM2 - GEM3 / mm: 2
GEM3 - GEM4 / mm: 2
Last GEM - Pads / mm: 2
Scaling: 1
☐ Last Strip ☐ Skirt ☐ 4 GEMs

Cluster Channel Mapping
CH Drift: 302
CH Last Strip / Skirt: 0 0
CH G1T / G1B: 303 304
CH G2T / G2B: 305 306
CH G3T / G3B 307 308
CH G4T / G4B: 202 203

Ramp Speed / V/s: 5

```
3/12/2025 3:17:10 PM: Bonn HV Control 5.4 loaded
3/12/2025 3:17:11 PM: MPOD: connected / main switch on
3/12/2025 3:18:04 PM: user: ramping channels 301 (50V, speed: 5V/s)
3/12/2025 3:19:46 PM: user: ramping down all channels (speed: 5V/s)
3/12/2025 3:19:49 PM: user: ramping channels 302 (50V, speed: 5V/s)
3/12/2025 3:20:30 PM: user: ramping down all channels (speed: 5V/s)
3/12/2025 3:20:33 PM: user: ramping channels 303 (50V, speed: 5V/s)
3/12/2025 3:21:39 PM: user: ramping down all channels (speed: 5V/s)
3/12/2025 3:21:43 PM: user: ramping channels 304 (50V, speed: 5V/s)
3/12/2025 3:22:07 PM: user: ramping down all channels (speed: 5V/s)
3/12/2025 3:22:09 PM: user: ramping channels 305 (50V, speed: 5V/s)
3/12/2025 3:22:51 PM: user: ramping channels 301 (3000V, speed: 5V/s)
3/12/2025 3:22:56 PM: user: ramping channels 301 (3050V, speed: 5V/s)
3/12/2025 3:25:23 PM: user: ramping channels 301 (3080V, speed: 5V/s)
3/12/2025 3:28:30 PM: user: ramping channels 301 (3080V, speed: 10V/s)
3/12/2025 3:36:52 PM: user: ramping channels 301 (3120V, speed: 10V/s)
3/12/2025 3:49:32 PM: user: ramping channels 301 (3125V, speed: 10V/s)
3/12/2025 3:59:00 PM: user: ramping channels 301 (3140V, speed: 10V/s)
```

Bonn HV Control v5.5

Figure 10: Screenshot of the slow control.
Yellow box: Here, you can adjust the voltage settings of your detector. The distances and the mapping is already set correctly, you just need to modify the voltages and fields.
Green box: After you set the voltages of your detector, click on “Ramp it!” and the detector ramps up. We recommend to use $5\,\mathrm{V\,s^{-1}}$ to $10\,\mathrm{V\,s^{-1}}$.
Red box: Our slow control can only handle a single-sided drift foil. In this detector, we are using a double sided drift foil. Therefore, you have to manually ramp channel 301 (where the top side of the drift foil is connected to) to the same voltage that is applied to channel 302.
Pink box: Here you can easily observe the current status of all channels that you power. Always observe if the set voltage and the read voltage is the same after the ramp is done (if this is not the case, immediately inform your tutor). You should also check the current, which is the current caused by the resistor to ground.

If you see a clear signal on the oscilloscope, you can exchange it with the MCA that is connected to your computer. Now you can measure pulse height spectra as described in section 3.3.

Tasks

1. Measure a reasonable double-spectrum. Which gain does the GEM have?
2. What is the dependency of the GEM gain on the applied voltage? Note that only a very limited voltage range can be scanned.
3. If you already simulated the gain of a GEM, how do your results compare to the measurements?

   If you did not do the session about simulation, yet, write down your findings and compare them later.
4. Once you have a gain value for a specific GEM voltage, you can also reduce the voltage of the MicroMegas such that only the GEM+MM spectrum is visible. This does not change the gain of the GEM. Save this spectrum.

   If you now increase the GEM voltage, you can compare the peak position to the one you just saved. How can you now calculate the gain of the GEM? With this method, you can extend the measurement range for higher GEM voltages. You can go up to ≈ 350 V.
5. Go back to a setting where you can observe a double spectrum. Increase the field between GEM and MicroMegas. What happens with the gain of the GEM? How can this be explained?

4 Third Session - Simulation of a GEM Detector

In order to simulate gaseous detectors, the powerful framework Garfield++ [Vee98, Sch12, Sch25] is widely used. With it, you can microscopically track electrons during the drift and amplification processes. In this exercise, you will simulate the gas gain of a single GEM foil for different voltage settings. You can use the code that we provided on the laptops. An exemplary simulation result is shown in fig. 11 where the trajectories of electrons and ions of an avalanche in a GEM hole are shown. After this session, you should be able to produce such a picture by yourself.

In order to run the simulation, you should first create a folder for your programs and results. Afterwards, you can extract the tar-archive which is located in the home folder of your machine to your personal folder. Then you can start with the compilation of the code. For this, we are using cmake and make. Last, we can start the simulation.

If you want, you can use the following commands to set up your working environment, compilation of the code and first execution of the code. Please note that the code should run "out of the box", but you need to think a bit how to adjust it to complete the tasks (see below). The last command starts the simulation with a GEM voltage of 350 V with 1000 initial electrons. Note that the initial electrons are treated individually which means that they get simulated one after the other.

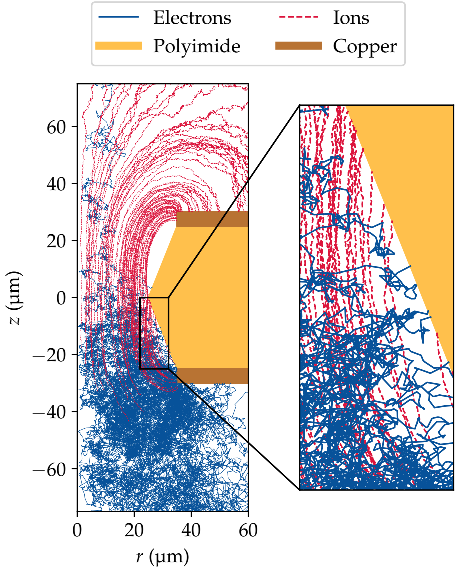


Figure 11: Simulation of an avalanche in a GEM created by a single incoming electron.

```
cd $HOME
mkdir mustermann # change mustermann to e.g. your familiy name
cd mustermann
tar -xvzf ../Terascale_Simulation.tar.gz
cd Terascale_Simulation
mkdir build
cd build
cmake .. -DCMAKE_INSTALL_PREFIX=..
make install
cd ..
./gem 350.0 1000
```

The simulation of the gain relies on the knowledge of the electrostatic environment. For this, we provide you the so-called "field maps" which have been calculated by ANSYS before. ANSYS is a commercially available program that uses finite element methods (FEM) to calculate the electrostatic potential on a mesh. The results of these calculations are stored in the mentioned field maps, which can then be loaded by Garfield++. The following lines are used to load the four field maps (the variable "vGEM" will be set to the GEM voltage that you want to analyse).

```
ComponentAnsys123* fm = new ComponentAnsys123();
const std::string efile = "ANSYS_Files/UGEM_" + vGEM + "/ELIST.lis";
const std::string nfile = "ANSYS_Files/UGEM_" + vGEM + "/NLIST.lis";
const std::string mfile = "ANSYS_Files/UGEM_" + vGEM + "/MPLIST.lis";
const std::string sfile = "ANSYS_Files/UGEM_" + vGEM + "/PRNSOL.lis";
fm->Initialise(efile, nfile, mfile, sfile, "mm");
```

The files have been calculated for a GEM with a drift field (above the GEM) of 400 $\text{V}\,\text{cm}^{-1}$ and an extraction field (below the GEM) of 2000 $\text{V}\,\text{cm}^{-1}$.

Another important aspect for the simulation of the gain is the gas composition and the corresponding properties, like for example the Townsend coefficient. Garfield++ interfaces Magboltz [Bia99, Bia24], which is a widely used database for cross sections of different interactions of electrons with gas. From these cross sections, Garfield++ computes the relevant properties. Therefore, in the code, you only have to write these lines to set the gas composition to Ar/CO_2 in the mixture of 70:30 at room temperature and at normal pressure.

```
MediumMagboltz* gas = new MediumMagboltz();
gas->SetComposition("ar", 70., "co2", 30.);
gas->SetTemperature(293.15); // Kelvin
gas->SetPressure(760.); // Torr
```

After these two important steps (and a few other necessary steps, that we do not have the time to explain in more detail), the avalanche of a single starting electron can be initiated. This is done via the “AvalancheMicroscopic” class. In this approach, the electrons are tracked from collision to collision. It is therefore a very precise function to simulate the behaviour of electrons in a GEM. The avalanche is only tracked in a so-called “sensor” which is a volume that has to be set before. The variables “x0”, “y0” and “z0” are the starting position of the avalanche, “e0” defines the initial energy of the particle. Furthermore, you could define a direction in which the particle moves initially, but we do not need this in this exercise and set these values to 0.

```
AvalancheMicroscopic* avalElectron = new AvalancheMicroscopic();
avalElectron->SetSensor(sensor);
avalElectron->AvalancheElectron(x0, y0, z0, t0, e0, 0., 0., 0.);
```

With this object, you can now do plenty of interesting things. First things first, we want to know the gain of the single electron. We can retrieve this value with the function

```
int np = avalElectron->GetNumberOfElectronEndpoints();
```

Now, we can also loop over every electron in the avalanche and extract for example the start and end position. The start position is basically the location where the ionisation happened. The end position can be either an electrode (upper or lower metal surface), the polyimide or the electron can get transferred to the next stage (e.g. to the readout).

```
for (int j = 0; j < np; j++) {
    // Get start (1) and end (2) points and information of the jth electron
    avalElectron->GetElectronEndpoint(j, xe1, ye1, ze1, te1, e1,
                                         xe2, ye2, ze2, te2, e2, status);

    // Electron on polyimide:
    if (ze2 > -kapton / 2. && ze2 < kapton / 2.)
        {sumElectronsPolyimide += 1.;}
    // Electron on upper metal:
    else if (ze2 >= kapton / 2. && ze2 <= kapton  / 2. + metal)
        {sumElectronsUpperMetal += 1.;}
    // Electron on lower metal
    else if (ze2 <= -kapton / 2. && ze2 >= -kapton / 2. - metal)
        {sumElectronsLowerMetal += 1.;}
    // Electron was transferred and therefore it participated in the effective gain:
    else if (ze2 < -kapton / 2. - metal)
        {sumElectronsTransfer += 1.;}
    else
        {sumElectronsOther += 1.;}
    sumElectronsTotal += 1;
}
```

And from these values, you can calculate the effective and total gain of the GEM, as well as the collection efficiency ϵ_{coll} and extraction efficiency ϵ_{extr}. The latter two describe the probability that an electron is entering the hole and leaving the hole, respectively.

Final remark: There is a very well written guide to Garfield++. You can find it on your machine, it is in the tar-archive that you extracted at the beginning of this exercise.

Tasks

1. Simulate the effective and total gain for different voltage settings. Which dependency do you find? What is the (statistical) uncertainty of the simulation?

2. If you already completed the session about the characterisation of the detector, does your simulated gain matches the measured gain? Remember: In the triple GEM detector, you had three GEMs at different voltages. For the measurement with the hybrid detector, you can directly compare.

   If you have the session still ahead of you, write down the dependency of the gain with respect to the voltage and compare later.

3. Where are most of the ionisation processes happening? For this, you have to modify the program a bit in order to write out the points of ionisation. The points are already stored in the vectors `_IonisationXPos`, `_IonisationYPos` and `_IonisationZPos`.

   Remember: You are working with C++, so you have to compile the code again, whenever you change something about it.

4. Try to draw the trajectories of the electrons that are created in one avalanche. Here, you should reduce the number of initial electrons to 1. Then you can adjust the code so that during the loop over every electron, you access the drift line points via

   ```
   avalElectron->SetCollisionSteps(1);
   avalElectron->EnableDriftLines(1);

   int nDriftLinePoints = avalElectron->GetNumberOfElectronDriftLinePoints(j);
   for (int driftLinePoint = 0; driftLinePoint < nDriftLinePoints;
           ++driftLinePoint) {
       double x,y,z,t;
       avalElectron->GetElectronDriftLinePoint(x, y, z, t, driftLinePoint, j);
   }
   ```

   These points (x, y, z and t), you can write to a file and draw them.

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