# Investigation of Electric Sparks on the Failure of GEM Detector Prototypes

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# TABLE OF CONTENT

## ABSTRACT

University of Texas at Arlington, High Energy Physics (HEP) group has been developing Gas Electron Multiplier Digital Hadron Calorimeter (GEM-DHCAL) since 2011. A series of radioactive source, cosmic ray and beam test measurements were performed on several prototype chambers in 2011 and early 2012. During the measurements, gradual deaths or permanent damage of the electronic readout pixels in the prototypes were observed. Electrostatic discharge (sparks) produced in the prototypes were suspected to be the most probable cause of the electronic failure. A detailed study in the prototype chambers were carried out by using the data from those measurements and certain pixels of the prototype were found to be abnormally active. Through chronological data analysis, this research implements statistical method to create a model to understand the behavior of the noisy pixels under the influence of sparks. Our study aims the better understanding of the sparks on DHCAL readout system to avoid the failure of the electronic in the future.

*Keywords*: DHCAL, Electric Discharge, GEM, Noise, Pixels

## Investigation of Electric Sparks on the Failure of GEM Detector Prototypes

University of Texas at Arlington, High Energy Physics group (HEP) has been working on the development of Gas Electron Multiplier (GEM) detectors for past several years. Several experiments with different types of radiations were performed on those detector prototypes. However, during the experiments performed during the summer of 2012, the prototypes failed. The students and the then researchers suspected electric sparks to be the most probable cause. This research is mainly focused on the behavior of electric discharges on those prototypes and its immediate or gradual effect on the prototype.

## GAS ELECTRON MULTIPLIER DIGITAL HADRON CALORIMETER (GEM-DHCAL)

All the Gas Electron Multipliers detectors work on the principle of Ionization, Drift, Multiplication and Charge collection/signal induction (Serge). Ionization occurs in between the enclosed area of the upper and lower part of the detector when radiation passes through the detector and interacts with the gas ions inside it. Through primary and secondary ionization, the ions are produced inside and charged particles drift towards the detector pixels where the electric field is very high (drift electric field). Inside the holes, the multiplication of the ions/electrons occur when the electrons collide with other existing gas particles. This multiplication nearly occurs in an exponential manner.

Then the charges are collected in the electrodes in the two end of the detector. These charges when collected causes the signal induction.

The DHCAL developed by UTA HEP implements the GEM technology. The Digital Hadron Calorimeter is a device which measures the energy of the Hadron particles. Since it implements the GEM technology, it operates on low HV, shows fast response in terms of signal processing (17-20 nanoseconds time delay between the trigger and hit information registration), and it is less expensive to manufacture.

## ELECTRIC DISCHARGE IN GEM-DHCAL

Electric discharge occurs when there is a connection between cathode and anode by inter-connected ionized gas particles.

Since, the signal induction in GEM works by amplification of charges, the quantity and energy of the charged particles/ions makes the DHCAL vulnerable to electric discharge or sparks. Inside the GEM holes, the transfer electric field is given by:

$$E=\frac{V}{d}[1]$$

Where,

E = Electric field

V = potential difference between the cathode and the anode

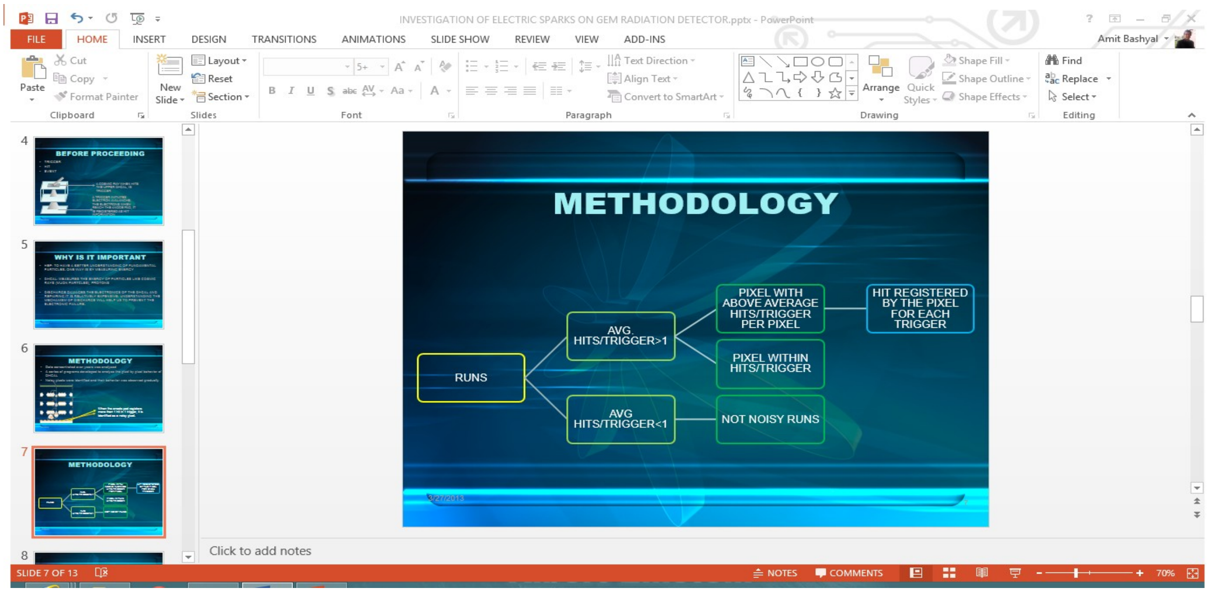
d = distance of separation between the cathode and the anode.

So, the electric field is directly proportional to the potential difference applied (in case of GEM-DHCAL developed by UTA, the potential difference applied was almost equivalent to 1920 V) and inversely proportional to the distance between the cathode and anode. In case of the transfer electric field inside the GEM foil holes, this distance is the thickness of the foil itself. So, thinner the foil, higher is the transfer electric field and hence the amplification of charged particles.

In case of capacitors, separated by air media, the increase in potential difference and the decrease in gap between two capacitors increases the electric field strength. At normal temperature and pressure, the air acts as a good insulator. Even at normal temperature and pressure, as the electric field becomes stronger, the number of charged particles ionized by collision with electrons also increases which is amplification. As the amplification increases, assuming the capacitor is performing at 1 atm. pressure, if the charge carrier number exceeds $10^8$ (Aston), the streamer is initiated and hence the electric discharge occurs. I personally studied this phenomenon to develop a concept on the mechanism of discharge in the GEM-DHCAL. Similar to the capacitors, the detector has two faces which has a potential difference of 1920 Volts. A discussion on the Kanal mechanism of spark studies can be quite relevant to understand the mechanism of electric discharge.

## METHODOLOGY

The figure below summarizes the procedure followed for the data analysis:



METHODOLOGY

RUNS

AVG. HITS/TRIGGER>1

AVG HITS/TRIGGER<1

PIXEL WITH ABOVE AVERAGE HITS/TRIGGER PER PIXEL

PIXEL WITHIN HITS/TRIGGER

NOT NOISY RUNS

HIT REGISTERED BY THE PIXEL FOR EACH TRIGGER

**Fig [1]. Summary of Data Analysis Procedure**

Mathematically, we can form a basis to identify how noisy a particular run is, by using the following relation:

$$N_{Hit/Trigger} = \frac{\frac{Hits}{Trigger}}{N_{Pixels}} [2]$$

Where,

$N_{Hits/Trigger}$ = Average number of hits/trigger for a particular run

Hits = Total number of hits registered in the run

Trigger = Total number of triggers registered in the run

$N_{pixels}$ = Total number of active pixels of the detector in the run (There are altogether 256 pixels in the detector prototype with 16 X 16 dimension).

Similarly, we can determine how noisy a particular pixel is by using the following relation:

$$N_{\frac{Hits}{Trigger}(x,y)} = \frac{Hits_{(x,y)}}{Triggers}\,[3]$$

Where

$N_{\frac{Hits}{Trigger}(x,y)}$ = Hits/Trigger for a particular pixel (x,y).

$Hits_{(x,y)}$ = Total number of hits registered by the pixel (x,y).

Triggers = Total number of triggers registered for a particular run.

The hits/trigger for a particular pixel gives a normalized value which can be compared with other pixels and make a comparative analysis of the level of activeness of pixels of the prototype.

## 1. DATA IDENTIFICATION

The data gathered during the past experiments are saved in the data concentrators (in short DCON) of the lab computer. Those past data, references from the DCAL logbook maintained by the previous research students are main basis of the spark study. From the data, we can recreate the event that occurred in the detector prototypes.

There are mainly three types of run data in the DCON:

1. Threshold Scan run
2. Internal Trigger run
3. Cosmic run/External trigger run

The threshold scan run is performed to determine the optimum threshold of the detector. The threshold of the detector is determined with the objective of cutting off electronic noise (which should be below the threshold strength) and detecting the signal from the original trigger. The threshold scan runs can be identified by a large number of hits and 0 triggers in the Lego plot generated when running the “hitMapHisto” command.

The next one is the internal trigger run. The internal trigger scan is performed by generating artificial triggers to check if the pixels are performing properly.

The final one is the external trigger run. They are performed by putting the detector under the influence of external source like the cosmic ray, proton beam or other source of radiation which ionizes the gas inside the detector and initiates the electron avalanche and signal induction in the detector. The data from the cosmic runs are basis for studying the electric discharge because during the cosmic runs, the incoming radiation are strong enough to ionize the gas particles. It is hoped that more clues on the electric discharges can be found in the cosmic ray data than the previous two types of data.

## 2. DATA ANALYSIS

Initially, data analysis was attempted to be performed through the existing programs used in the lab computer. However, it was soon realized that in order to recognize the actual hit information registered by the pixel for a particular trigger, a separate algorithm should be developed. Before developing the code, the data contained the hit information which also consisted the hit information due to the electric noise. The only way to determine the true hit information from the noise was the time lag between the trigger registration and the signal induction (hit information registration). In the case of the DHCAL, the time lag was between 17-20 nano second. Based on this, with the help of Dr. Seongtae Park, a C++ code was developed to mask out the hit information from the raw data which were outside this range. Then, again a set of codes were built to analyze the hit information registered by individual cells for a particular trigger. Only then, it was possible to actual behavior of cells during the runs.

# RESULT

The result is divided into 2 parts. The first part consists of the results from the data analysis before writing the code to analyze the pixel by pixel behavior of the detector. The second part consists of the result after developing the code.

## 1. BEFORE WRITING THE CODES

Earlier analysis were carried out using the lego plot generated from the hitMapHisto of the lab computer. It gave basic information like the total number of hits registered in each cell, the total number of triggers and packages. The hits/trigger per pixel for particular pixel were plotted for a number consecutive runs and its gradual behavior was studied and compared with other pixels.

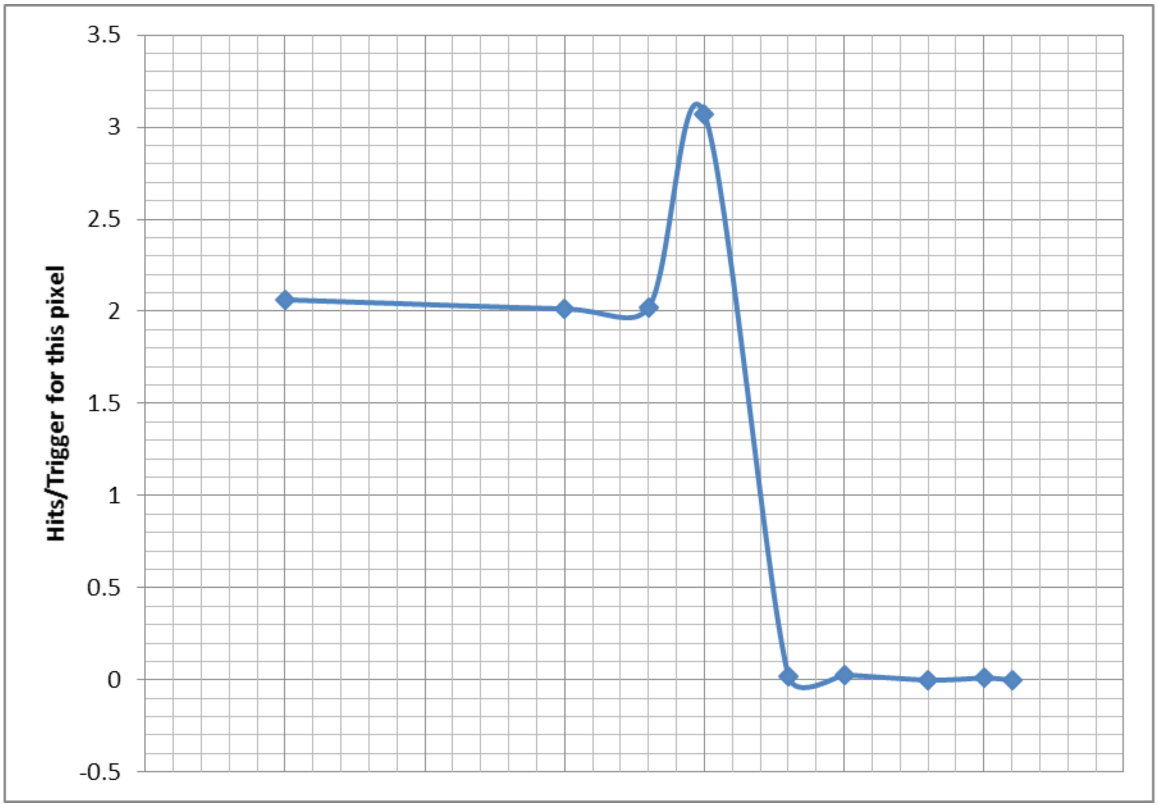


**Fig [2]. Hits per trigger for pixel (7,7) on a particular set of runs.**

In the figure, the high number of hits/trigger is mainly due to the mixing up of electric noise with the genuine hit information which can only be separated from the time lag between trigger registered and the hit information recorded for a particular pixel. However, this graph shows that the cell was particularly less active (if neglecting the effect of electric noise) for first three runs and then it's activity increased exponentially in the fourth run and then dropped down to almost 0. Preliminary results inspired to look at the similar behaviors for other pixels also. The sudden drop of the pixel's activity showed the hint of the pixel's inactivity. Latter analyses were centralized around this pixels and its neighborhood. However, no hints of electric discharge or any peculiar mechanism that would suggest the discharge appeared.

## 2. AFTER THE DEVELOPMENT OF CODE

After the codes were written in early January of 2013, a pixel by pixel analysis of the detector after masking out the electric noise was possible. It drastically decreased the hits/trigger ratio for each pixels and the overall run as a whole. Also, an additional code was written to trace down the behavior of each pixel in each trigger of a particular run. This allowed to see how the activity of pixel changed over time for a same run.

The pixel by pixel analysis for the noisy run showed some important results:

1. Noisy pixels are those pixels which register high hits/trigger per pixel for almost every runs (if not kill masked or the threshold is kept constant). To generate a high hits/trigger, a pixel must fire more than once and register multiple hit information for a single trigger.

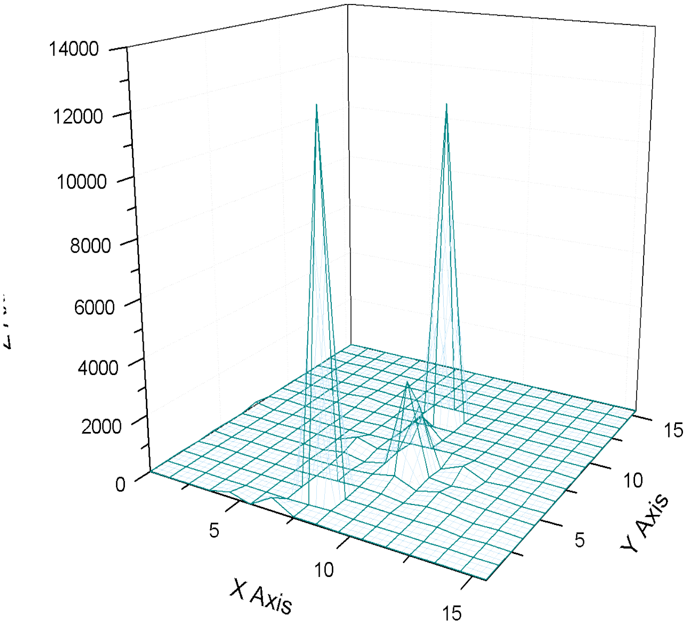


**Fig [4]. Hits registered by normal pixels and the noisy pixels.**

In figure [4], the height of the spikes represents the hits/trigger for a particular pixel. Each square boxes on the XY plane represents the pixels. The high spikes on the two sides are because the two pixels in these reasons were particularly active and perhaps noisy. The hits/trigger registered by the normal pixel in the middle portion of the pixel shows that compared to the normal pixels, noisy pixels are identified by high hits/trigger and this graph only includes the hits registered within the range of 17-20 nanoseconds. A thorough analysis of raw data will show that these two noisy pixels registered multiple hits/trigger several times and hence the height of the peaks is greater than that of normal pixels.

2. If multiple hit information are registered within the time frame of 17-20ns, we have a high probability of the pixel being affected by external sources also (including electric discharge). However, if a pixel registers double hit in a single trigger, the time lag between the registration of 2 hits cannot be very large (usually 2-5 nanoseconds).

3. If we neglect the electric noise, the high hits/trigger is mainly concentrated within the shaded region. It is also mainly because most of the incoming radiations are focused inside the shaded region.

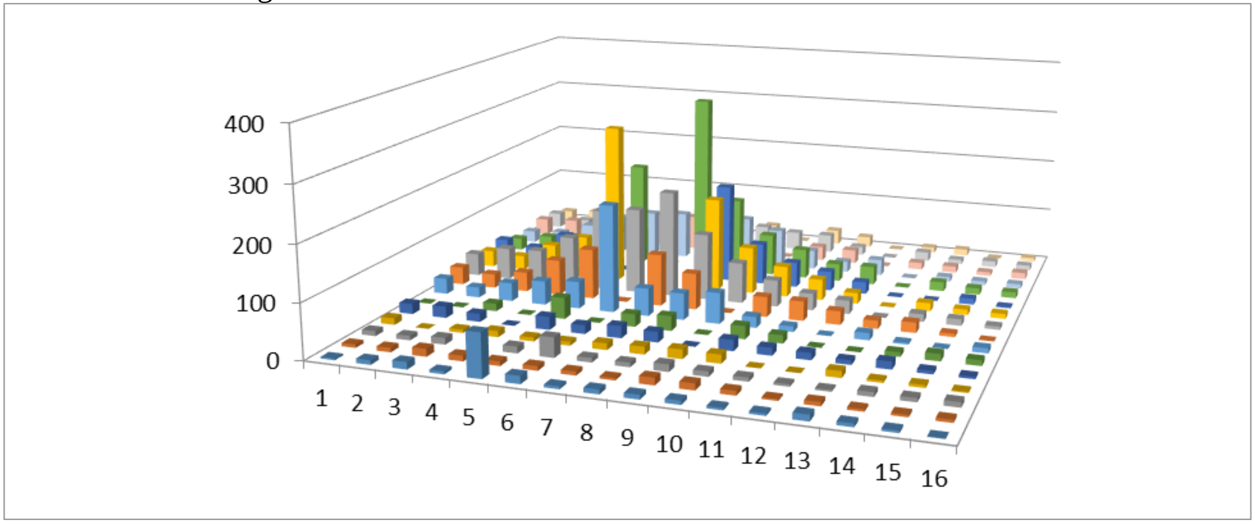


**Fig [5]. Hits distribution in a cosmic run**

From the figure, we can see that the most of the active pixels are concentrated in the middle portion of the detector prototype. There can be some active pixels on the edges also (as seen in (5,0)) which might be either because of the incident angle of the incoming radiation or because of the noise.

4. Also, some of the earliest inactive/dead pixels were observed inside the shaded region. Since the shaded region was the region of the detector which showed relatively higher activity.
5. Usually, inactive and noisy pixels are found in clusters inside the shaded region. This might be either because those groups of pixels were found to be noisy and hence kill-masked or they were completely inactive by that time. Either way, it suggests that if electric discharge occurs in a region, it affects the electronics of the neighboring pixels also.

## SPECIAL OBSERVATIONS

During the data analysis of internal trigger runs, some interesting data were seen. According to the data, there were several incidents when the trigger registered and the hit registered by a particular pixel (in DCON 1 and 2) were almost at the same time. Also, there were also instances, when a particular pixel registered hit information for the same trigger, "more than one time" at the same time. Although one possible explanation can be because the pixels were very active at the internal trigger run (which is meant to be to know if the pixels are active or not), the process of hit registration by the pixel occurred faster than the time required for the machine to process the trigger information and the hit information.

When most of the pixels in the DHCAL chambers were dead, chamber 1 was switched to chamber 1 in 7-17-2012. The last cosmic run before the switch was 203134. In run 203123 which was done for approximately 7.5 hours, the output file was reported to be very large (approximately 400 MB) with only 135 active pixels(out of 256). The hits/trigger was only . A bad kill mask (-n19 was applied) was 0.37. A bad kill mask is suggested to be the cause of the corrupt file. The next cosmic run 203124 had a lower threshold (-n10) and it also had a very large file. After the chamber was switched, a cosmic run was again conducted (run 203135). However, the cosmic run showed a very low hits/trigger (0.01). Improper power cycle was suggested as reason behind the failure. However, the raw data from this run was small enough to be analyzed. A detailed analysis of 3 pixels were done—(5,5), (6,6) and (8,6). The analysis showed some interesting result:

1. All the pixels were very active at the beginning sometimes registering multiple hits in the same trigger.
2. All the analyzed pixels were active exactly upto 209th trigger.
3. From 210th trigger and onwards, no hits were registered.

A combined figure of the frequency of hit registration of these 3 pixels is shown below:

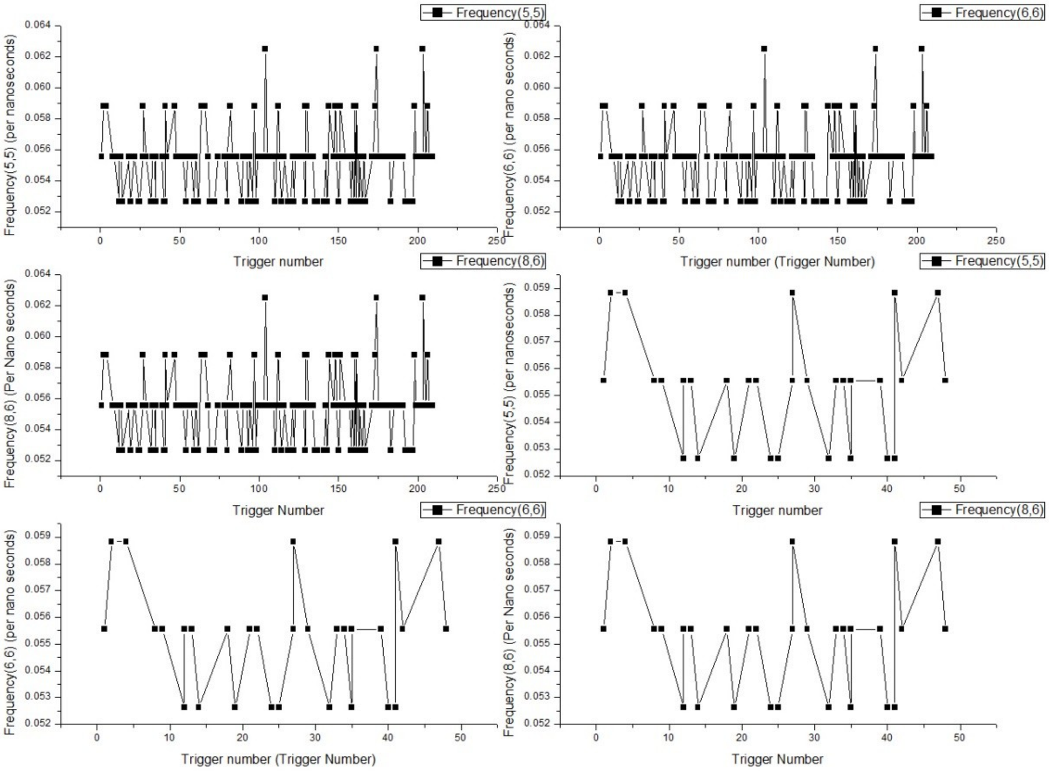


**Fig [6]. Frequency of appearance of 3 pixels**

**1st 3 graph represents the frequency of hit registration for all triggers**

**2nd 3 graphs represent the frequency of hit registration for 1st 30 triggers**

From, the graph it can be seen that the almost all the pixels had shown almost similar behaviors. Until they appear, all the pixels were abnormally active which is possible due to very high electric noise caused by high voltage. Again, most of the active pixels are concentrated in the shaded region.

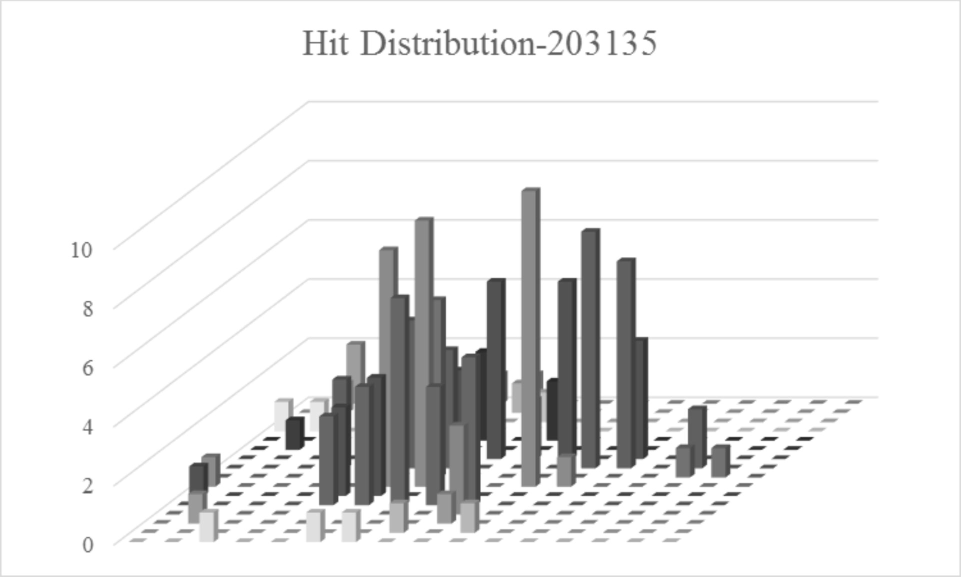


**Fig [7]. Hit Distribution in Run 203135**

## CONCLUSION

A thorough analysis of the run 203135 shows that the failure of the DHCAL system occurred suddenly. For a GEM chamber failure, we might expect strong signals from the pixels. The observed abrupt failure of the system after 210th trigger shows that the failure of the DHCAL system was caused by the damage in the electronics rather than the GEM itself. One more evidence to support the failure of the electronics is that although the hit registration is not observed after 209th trigger, the GEM foil was still registering the trigger.

Run 203135 was the first run to be conducted after the GEM 3 and GEM 1 chamber were switched because GEM-1 was thought to have failed. The last few cosmic runs conducted on GEM-1 have very large data. After switching the GEM chambers, in the run 203135, had the electronics not failed, looking at the activeness of the DHCAL pixels, we can suppose that the data file for that run also would have been very large.

Finally, observations show that the failure of our DHCAL is triggered by the improper power cycle. There could have been a high potential difference applied. The level of noise in the last run gives strong evidence of high potential difference. The electric avalanche turned into electric streamer might have generated the electric discharge which can be anticipated in high potential difference (and hence strong electric field). The abrupt failure of the system suggests the failure of the electronics rather than the foil itself.

## FUTURE WORKS

Although the observation suggests that improper power cycle might have been the reason behind the failure of the electronics, a gradual increase in the number of noisy pixels observed in the previous experiment is still to be analyzed. The frequency of registration of multiple hits at the time trigger for different runs for a particular pixel can show the evolution of the noisy pixels. A separate code needs to be written to trace down the frequency of the noisy pixels. After the end of semester, I am planning to work on it.

Also, I would suggest that the pixel by pixel analysis should be done every now and then, when the detector is run in future. Multiple hit registration in a single trigger in the run should be checked every now and then to ensure the proper functioning of the DHCAL system. This will help us keep track with the activity of the pixels and avoid potential electronic failure.

Similarly, the new logbook should include following information on each run:

1. Type of run
2. Pixels in which the kill mask was applied
3. Duration of the Run
4. Any peculiar behavior if observed during the run

Besides regular observations, if these information are included in the future runs, analyzing the past data can be faster and more efficient.

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