CERN Summer Student Programme 2018

Final Report

GEM Sustained Operations studies

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Introduction

During the Summer Student Programme I have taken part in the GEM Sustained Operation studies in CMS experiment. In particular, in collaboration with the CMS GEM group, I have carried out a series of tests on the VFAT3b_prot, the ASIC designed for the readout of GE1/1 detectors, mounted on the HV3b_V2 hybrid PCB, in order to identify the cause of the channel loss recorded in some GEM detectors installed for testing purpose in CMS in January 2017. The understanding of the process that leads to these losses is fundamental for the development of mitigation techniques.

1. GE1/1 project

1.1 Motivations for the upgrade

The Compact Muon Solenoid (CMS) experiment is located at point 5 on the Large Hadron Collider ring. It studies the particles produced in the collisions by employing several subsystems of detectors; among them a very important role is played by the muon system.
CMS will undergo several upgrades in the Phase-1, in preparation for the Run 3. During the Long Shutdown 2 (LS2) a double layer of triple-GEM detectors will be installed in the first endcap station of the CMS muon system (GE1/1). This will add redundancy to the muon system in the $1.6 < |\eta| < 2.2$ pseudorapidity region and it will improve the muon trigger and tracking performance during Run 3. The GE1/1 detector station is shown in the quadrant cross-section of CMS in Fig. 1.1.

Ten GE1/1 detectors were installed into the CMS endcap in January 2017 (*Slice test*) in order to study their integration in central CMS operations.

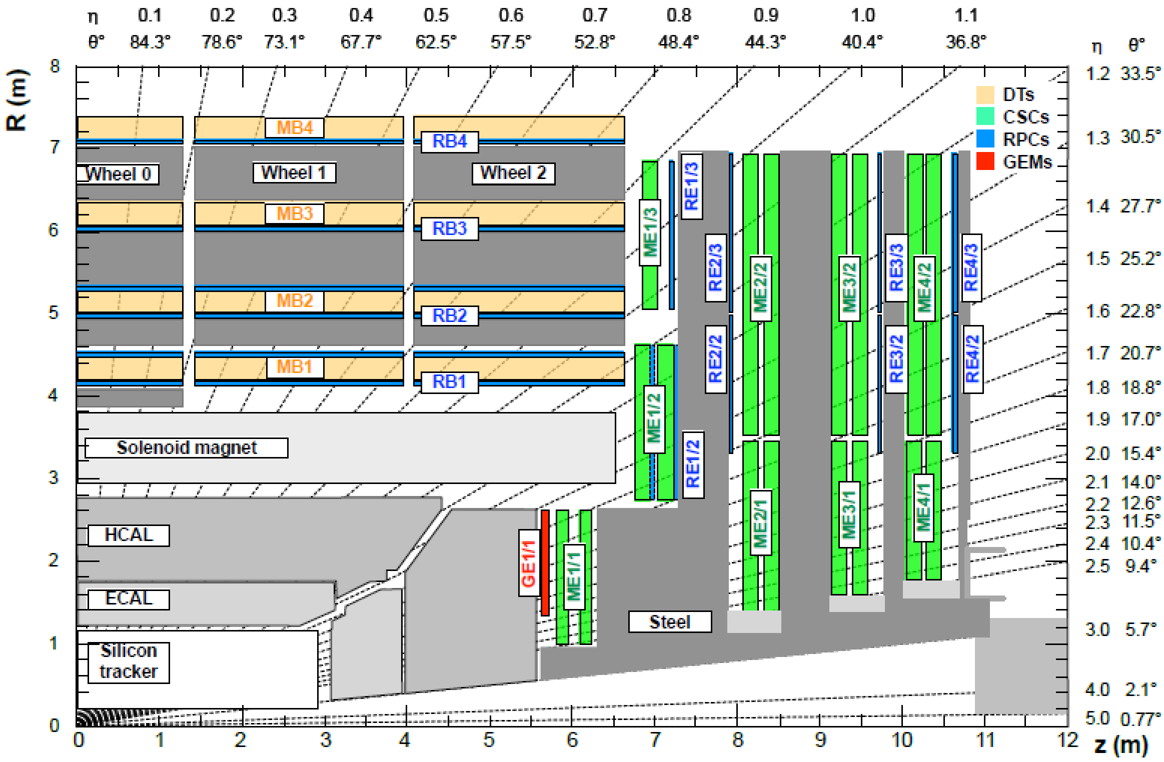

Figure 1.1: A quadrant of the CMS cross-section.The GE1/1 location is highlighted in red [1].

1.2 GEM technology

GEM (Gaseous Electron Multiplier) technology exploits electron amplification that occurs within a gas medium (70% Ar, 30% CO_2) inside narrow holes (50 μm diameter) that perforate a polyimide foil in a hexagonal pattern. The GEM foil is clad on both sides with thin conductive layers of copper. A voltage of a few hundred volts is applied across the two layers which creates a strong electric field inside the holes (~70 kV/cm) that causes avalanches in the gas.

An arrangement of three cascaded GEM foils, known as a "Triple-GEM detector" (see Fig.1.2), allows for modest high voltage and gas amplification across each individual foil to avoid electrical breakdown problems, yet provides a high total charge amplification factor (up to 10^5). This is because the gains of the individual foils multiply to produce the total gain. GE1/1 detectors will have a 3/1/2/1 mm drift/transfer1/transfer2/induction gap configuration.
The amplified charge induces a signal on the electrodes that are finely segmented (3072 strips divided in 8x3 partitions in $\eta - \phi$) and the induced charges are read out by sensitive electronics [1].

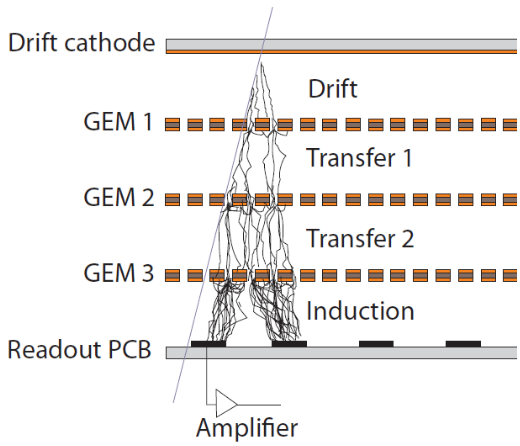

Figure 1.2: Triple-GEM detector schematic.

This kind of technology is able to sustain very high particle rates, up to 10 MHz/cm^2, featuring a spatial resolution of the order of 100 μm, a time resolution of a few ns (< 10 ns in order to contribute to CMS L1 trigger) and detection efficiencies above 98%.
All of this characteristics make the triple-GEM technology a very good candidate to be used in the forward muon spectrometer of CMS for future LHC runs, when one expects particle rates of several kHz/cm^2.

1.3 Electronics system

The architecture is composed of two regions: the "on-detector" and the "off- detector" region, that communicate via optical fibers (Fig.1.3).

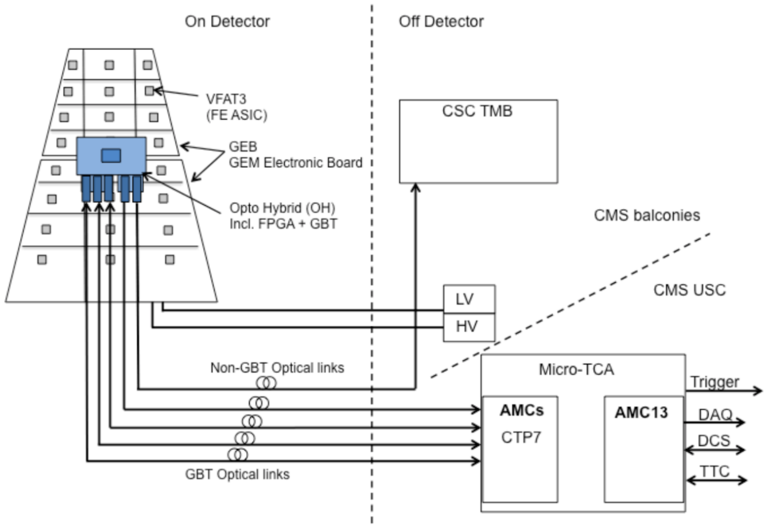

Figure 1.3: Electronics architecture (version 3) for GE1/1.

The GE1/1 readout is divided in 24 sectors, each having 128 strips.
The charge signals are amplified, digitized and processed by ASIC circuits (VFATs), mounted on a hybrid which plugs into the Readout Board connectors. The control and readout of the VFAT hybrids is delivered through the GEM Electronic Board (GEB). An opto-hybrid board also plugs into the GEB, which contains three Giga-Bit Transceiver (GBT) chip sets, a Field Programmable Gate Array (FPGA) and optical receivers and transmitters to the Off-Detector region.
The on-detector electronics are powered via ten FEAST DC-DC converters.

The off-detector electronics provides the interfaces from the detector to the CMS DAQ, TTC and Trigger systems, and is based on the μTCA standard.
The VFAT is the customized ASIC used for the readout of detector signals. Its block diagram is shown in Fig. 1.4.

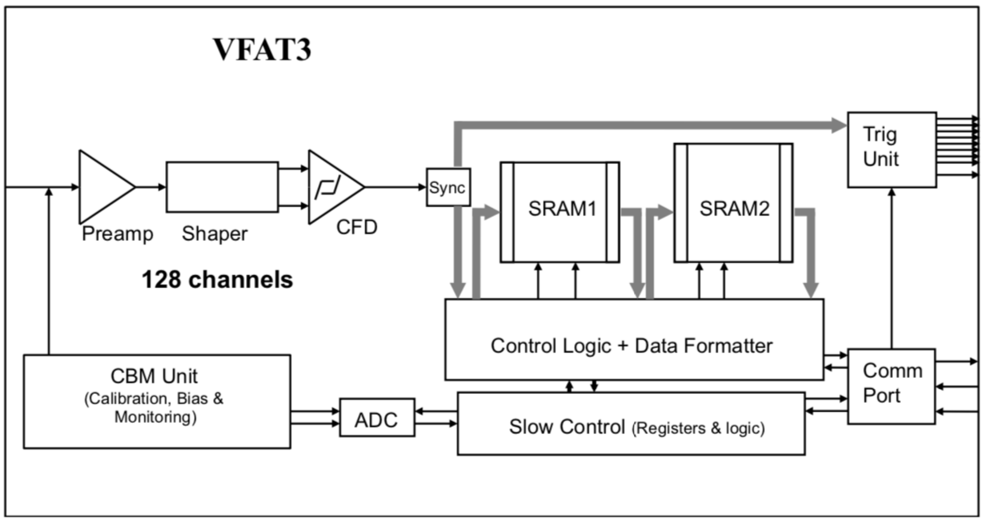

Figure 1.4: VFAT3 block diagram.

Each of the 128 strips, belonging to one sector of the detector and connected to one VFAT, has its own charge sensitive preamplifier, shaper and constant fraction discriminator (CFD). After this chain there is a synchronization unit that synchronizes the comparator result with the 40 MHz clock.
The data then splits into two paths, one with a fixed latency for trigger signals, and the second for tracking data which is at variable latency.
More details on VFAT3 and on the implementation of its CFD can be found in [2], [3] and [4].

2. GEM Sustained Operation studies

2.1 Motivations and goals

Slice test detectors were initially equipped with the version 2 of the electronics, and then, in February 2018, the electronics of two of them have been replaced with the version 3 (described in section 1.3), that has some changes with respect to the previous one in order to better fulfill CMS requirements.

During Run 2, a gradual irreversible channel loss in VFAT2 chips has been observed. The rate of this loss was different depending on the detector and also in the same detector over time.
Channels are defined *dead* if they show a level noise compatible to the one that characterizes the chip when it is disconnected from the detector. In fact, since the noise is proportional to the capacity, when the VFAT is detached from the detector the capacity is almost zero and the noise level is lower than in the case it is connected to the readout strips.
Data from slice test detectors showed a rapid drop in the noise for certain channels overtime.
Some of the damaged VFATs were examined under a microscope, finding that the inputs of the chips were burned away. A process that could cause this kind of damage is the flowing of a large current through the protection resistor at the input of the chip, which produces a great amount of heat that could not be dissipated in time and thus destroyes the resistor.

In order to better understand the process that has caused VFAT damages and to develop a more robust electronics, a R&D campaign called "GEM Sustained Operation" was launched at the beginning of the summer 2018. The main goal of the GEM Sustained Operation studies is to understand the cause of the channel loss in order to develop some mitigation techniques.
Different hypothesis aiming to explain the channel loss origin were formulated and several tests were performed in order to verify or reject them. Some possibile causes of channel loss could be:

1. improper detector operation (e.g. Low Voltage (LV) power failure) that potentially allows the anode to float toward the voltage of the bottom electrode of the third GEM foil, due to capacitive coupling,
2. high charge events due to Minimum Ionizing Particles (MIPs),
3. high charge events due to High Interaction Particles (HIPs),
4. discharges propagating to the anode plane.

2.2 Non Destructive tests

2.2.1 Measurements

The "Non Destructive" measurements were performed in order to test the hypothesis n.1, 2 and 4, explained in section 2.1.
A GE1/1 detector, equipped with the version 3 of the electronics, was split into three regions which have been operated under different test conditions for the VFATs, as shown in Fig. 2.1.
The noise of a VFAT channel can be characterized performing an "S-Curve", i.e. a routine consisting in the scanning of passing events for increasing amplitude of calibration pulses injected in the channel with respect to a certain comparator threshold. This gives a characteristic S-shaped curve that can be fitted with the error function: the value of the standard deviation represents the noise level of the channel.

As explained in section 2.1, the characteristic noise of channels attached to detector's strips is higher than that measured in the case of *Zero Input Capacitance* (VFAT channels detached). Therefore it is possibile to identify a dead channel by comparing its noise value with the ones characteristics of Zero Input Capacitance.

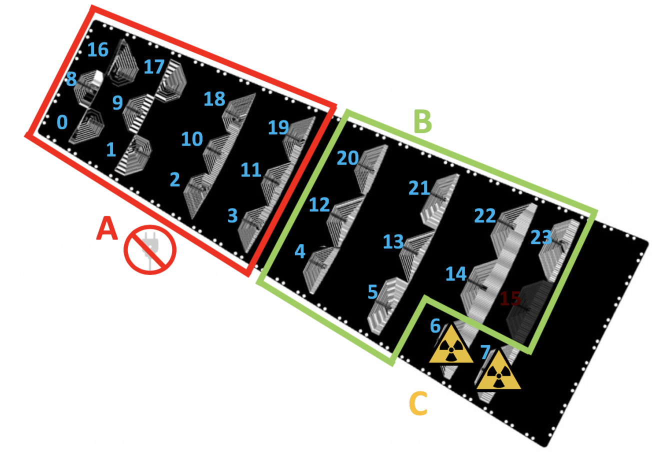

Figure 2.1: Different regions of operations for the VFATs: region A is red, region B is green and the region C is indicated with the symbol of radioactive source.

- **Region A: Test of "LV improper operation"**
12 VFATs are powered in an improper way: the High Voltage (HV) is left on while the LV is off.
The goal is to understand if an improper operation, like a LV failure, can cause channel loss.

- **Region B: Test of "Proper operation"**
9 VFATs are "normally" operated under cosmics.
The goal is to exclude the possibility that channel inputs can be burned by avalanches in normal operation.

- **Region C: "Irradiation test"**
2 VFATs are continously irradiated by 2 cadmium sources (Cd109) placed under the drift electrode.
The goal is to understand if channel loss can be caused by avalanches from "background" particles.

Before starting the test illustrated above, some S-Curve scans were performed in order to confirm the existence of a clear distinction between the noise levels in case of attached and detached VFATs, and then to establish the noise range values corresponding to a dead channel.
The results of these preliminary measurements, carried out for 21 VFATs, are plotted in Fig.2.2.
A channel can be considered dead if its noise value is in the range 0.1 - 0.4 fC (yellow boxes in the plot).
The lower bound is different from 0 in order to prevent failed fits from being included in dead channels.

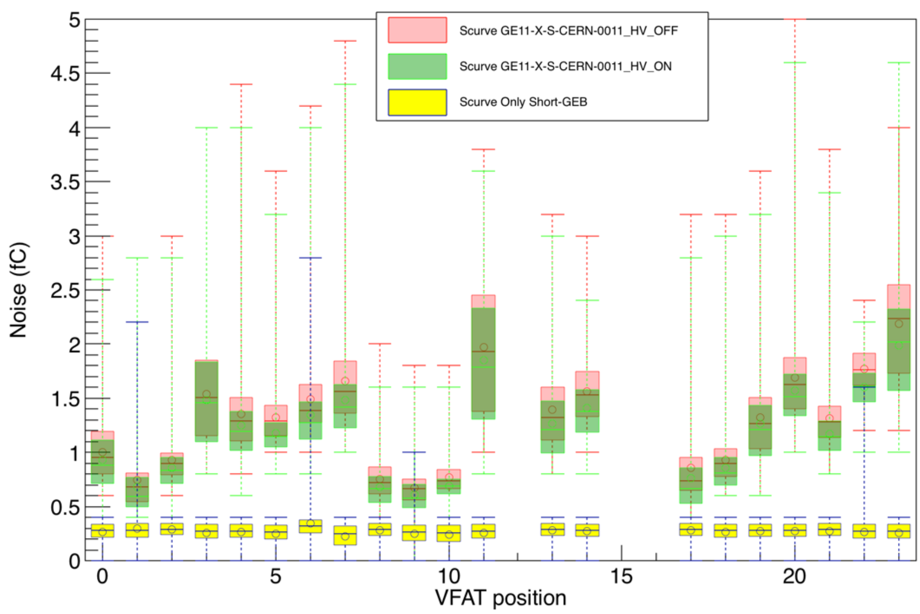

Figure 2.2: Noise comparison for three different cases: VFATs attached to the detector with HV on (green) and HV off (pink) and VFATs detached from the detector (yellow). The box represents the interquartile range, the dashed whiskers are the minimun and the maximum values, the horizontal line is the median and the circle is the average of the noise distribution per each VFAT. The arming comparator threshold used is 100 (DAC units).

After these preliminary measurements, the "Non Destructive" tests started: the VFATs were operated in the conditions described above, with an average gain of the detector of 10^4. A S-Curve was taken every day or every time an HV event, i.e. an OverCurrent or a trip, occurred (the maximum current was set equal to 2 μA). The Detector Control System (DCS) monitored the gas and the HV status of every electrode of the detector (independently), alerting the users with an email in case of anomalies.
This procedure was followed in order to detect channel losses and to identify eventual correlations with some types of HV events.

2.2.2 Results

The measurements were carried out during an effective period of 78 days. During all this time only 4 HV events occurred: 3 of them were characterized by a discharge that propagated inside the detector and reached the anode. After these events some channel losses were observed. In the other case, a discharge propagated only across GEM foils, not reaching the anode and no channel loss was recorded.
Apart from the losses due to these HV events, no damages purely related to avalanches in normal operation, to the irradiation or to LV improper operation were recorded.
An example of these results is shown in Figg. 2.3, 2.4, 2.5 and 2.6. Figure 2.3 is a DCS screenshot, capturing the OverCurrent event occurred on the 11th of July at 14.28. After this HV event, a sudden decrease in the noise value of some channels of the VFAT in position 10 was recorded. This behavior can be observed in Fig. 2.4 showing the noise value of the VFAT10 channels obtained from the S-Curves performed from the 8th July to the 31th of July. The dead channels are characterized by horizontal blue lines (corresponding to values of noise in the range selected before the beginning of the test). As it is possible to notice, the channel loss occurred on the 11th July.

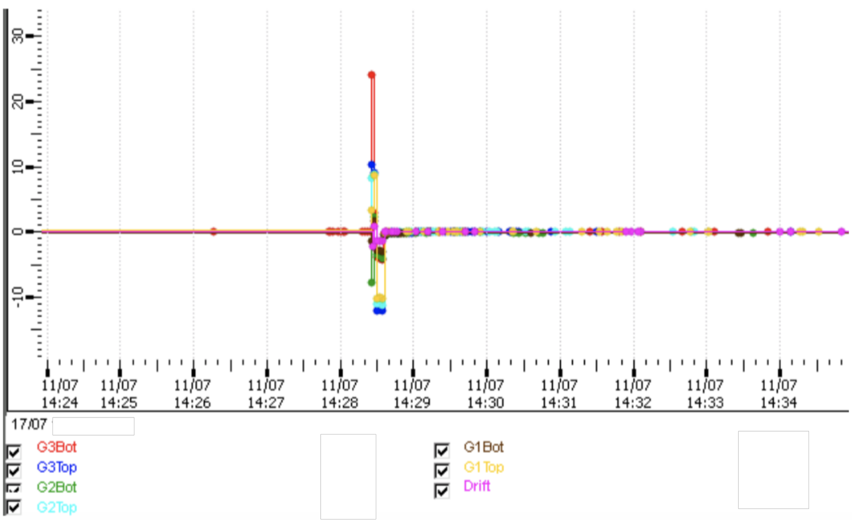

Figure 2.3: DCS screenshot showing the OverCurrent event occurred on the 11th of July at 14.28. On the y axis are represented the values of the current (μA).

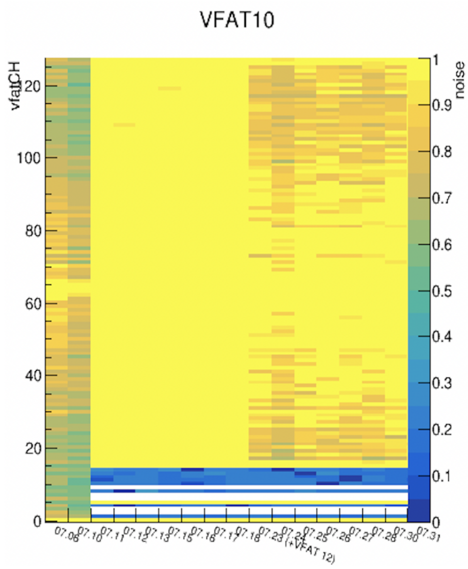

Figure 2.4: Summary of the noise of channels of VFAT in position 10 obtained from the S-Curves taken from the 8th to the 31th July.

A more clear comparison of the noise before and after the HV event is possible by looking at Fig. 2.5, that shows the noise values of the channels of VFAT 10 obtained from the S-Curve performed on the 10th July, and Fig. 2.6, that shows the results of the S-Curve taken after the HV event, on 11th July at 15.00.

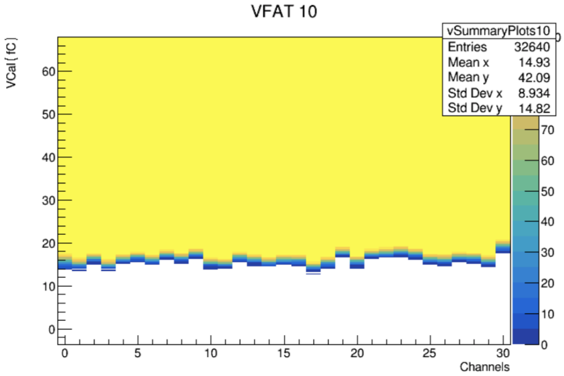

Figure 2.5: Noise values of VFAT10 channels in the S-Curve performed before the HV event.

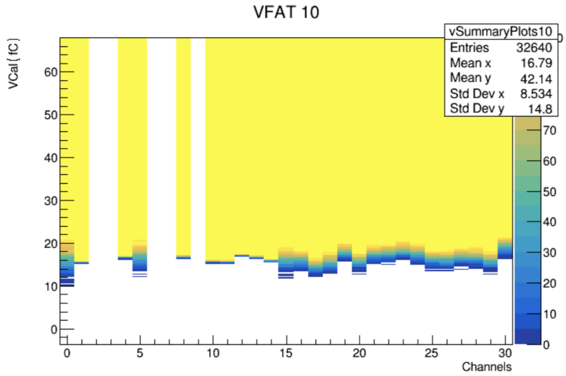

Figure 2.6: Noise values of VFAT10 channels in the S-Curve performed after the HV event.

Data recorded during “Non Destructive” tests shows a correlation between discharges reaching the anode and channel losses, supporting the hypothesis 4. On the other hand, no evidences were found in support of the hp. 1 and 2, which therefore have been rejected.

2.3 Destructive tests

2.3.1 Measurements

The “Destructive” measurements (called in this way because of the risk of damage to the detector due to very energetic discharges initiated with HIPs) were performed in order to test the hypothesis n.3 and 4, explained in section 2.1. These measurements were performed on a GE1/1 detector with a modified drift PCB: it was drilled in order to allow the penetration of alpha particles, produced by an Am241 source, inside the detector. The position 7 (sector $(i\eta, i\phi) = (1, 1)$) was choosen for the irradiation and the number of the channels corresponding to the strips facing the hole in the PCB in this position (i.e. the strips illuminated by the alpha source during the destructive measurements) was determined using a Fe55 source and acquiring the VFAT trigger data.
Then, the signal from the bottom electrode (with respect to the drift) of the third GEM foil (G3b) was sent to an oscilloscope and to a discriminator module in order to save interesting events and to count them. Moreover an antenna, realized with a short LEMO cable inductively coupled with G3b, was used to detect and count discharges, as explained in [5]. The detector was equipped with version 3 of the electronics. In order to be able to investigate expected damages under the microscope, some VFATs without a globe top protection (a cover put on the top of the ASIC) were used and they were mounted in the wider part of the detector, on the position 7 and on the closest ones.

Before starting the measurements, some S-Curve scans were performed with VFATs attached and detached from the detector, in order to estimate, as in the previous test, the noise values range in which a VFAT channel could be considered dead. The results of these preliminary measurements, plotted in Fig. 2.7, corfim the previous definition of dead channel (i.e. channel with noise value in the range 0.1 - 0.4 fC).

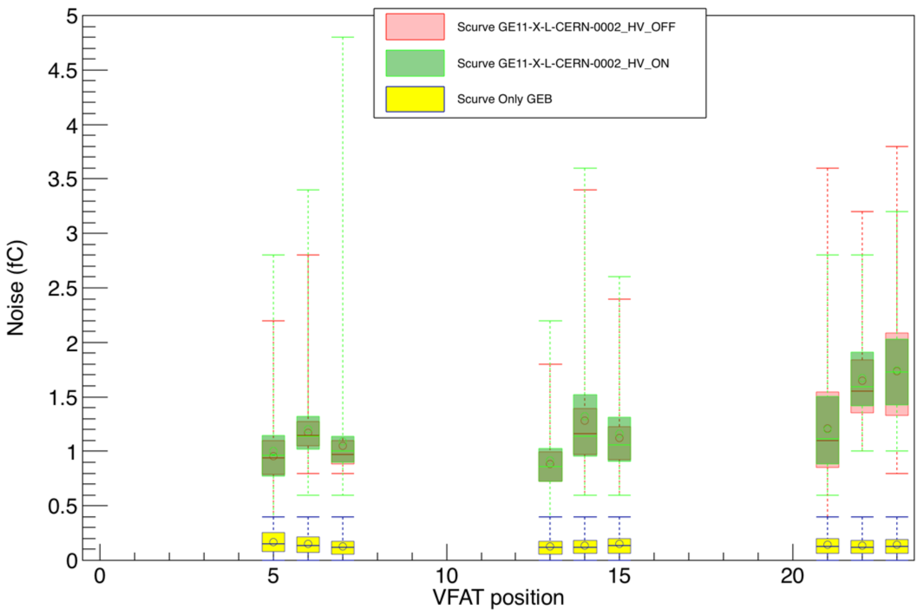

Figure 2.7: Noise comparison for case of VFATs attached to the detector with HV on (green) and HV off (pink) and of VFATs detached from the detector (yellow). The arming comparator threshold used is 100 (DAC units).

During the first measurement of the “Destructive” tests the detector was operated at an average gain of 10^4. The source, fixed on position 7, was shielded with a paper foil during S-Curve scans. A S-Curve was taken after ten minutes of irradiation or every time a HV event occurred and the number of events (i.e. avalanches triggered by HIPs) and discharges was counted with a scaler. After having collected at least 3 millions of events, the voltage applied to the detector was increased and all the measurements were repeated in correspondence of the new value of gain.

2.3.2 Results

In Tab.2.1 are summarized the results of the measurements performed for different values of gain. No channel loss was observed up to a value of gain of 10^5. Four discharges occurred at a gain of $6 \cdot 10^4$, but they didn't reach the anode and no channel loss were recorded.

Gain	Events (10^6)	Discharges	VFAT damaged ?
$1.0 \cdot 10^4$	8.22	0	NO
$2.5 \cdot 10^4$	3.25	0	NO
$6.0 \cdot 10^4$	3.23	4	NO
$1.0 \cdot 10^5$	1.03	Many	YES

Table 2.1: Summary of the results of "Destructive" tests.

Operating the chamber at a gain of 10^5, ten times bigger than the nominal value of GE1/1 detectors, many discharges occurred and some channel losses were observed in the S-Curve scans performed after the destructive events. In some cases, after the discharge, it was not possible to retrieve data from the VFAT in position 7 even if it still responded to Slow Control commands. Further investigation for why the digital side of the chip was damaged is needed.
The damaged VFATs were investigated using a microscope, finding that the channel inputs were burned away, as highlighted by red circles in photos in Figg. 2.8 and 2.9.

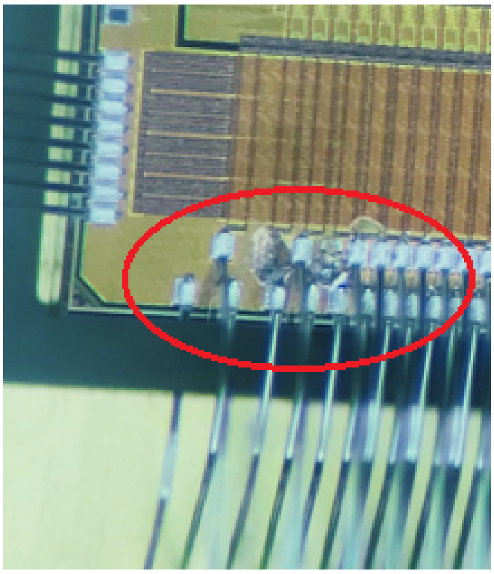

Figure 2.8: VFAT damaged after a very energetic discharge: the channel inputs were burned away.

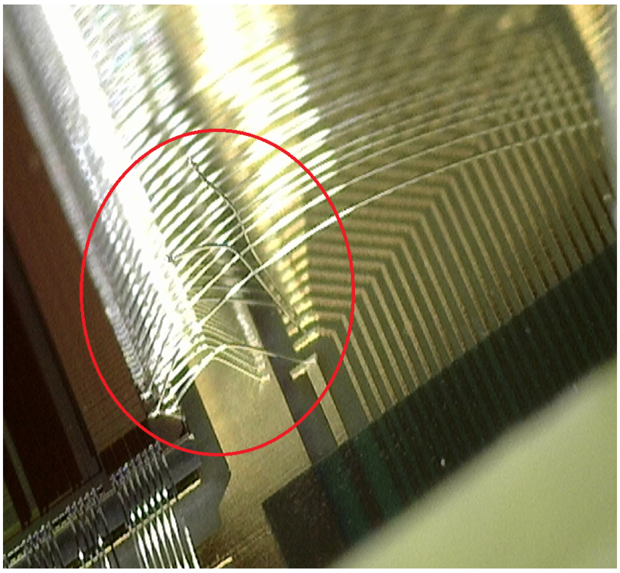

Figure 2.9: Evident damages to the channel inputs of the VFAT, which results to be no more connected.

Conclusions and future plans

The tests on the VFAT3b_prot ASIC, mounted on the HV3b_V2 hybrid PCB, carried out during the summer excluded the possibility that improper LV operations and irradiation from MIPs during normal operation can initiate discharges that lead to channel loss when the detector is operated at CMS nominal value of gain (10^4). Morever, it has been observed that very energetic discharges (that could be initiated by HIPs) reaching the anode can cause channel loss.

Further tests will be performed in the next future in order to completely validate these hypothesis and destructive measurements will be repeated with new versions of VFAT3, having additional resistors and diodes at the inputs of the channels, in order to select the most suitable and resistant one for the final GE1/1 electronics.

References

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