Development of a Spark-Detection System for the Quality Assurance of Large-Area GEM-Foils

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Abstract. Gaseous detectors based on large-size GEM-foils are planned to be used for a variety of upgrades and new experiments using high-rate and high-intensity particle beams. An excellent quality control of GEM-foils is a mandatory prerequisite to select the best foils for the assembly of a GEM detector. The high voltage stability of the foils is here of uppermost importance. In particular discharges that occur at the same position need to be detected. A spark detection system has been developed to automatically detect and record the time and position of sparks. The system is based on a commercial web camera installed in a housing for the tests and a custom-made, LabVIEW-based software for control and operation. An automatic Spark-Detection System for GEM foils was designed, built and characterized. It is able to detect and record discharges in large-size GEM foils during the quality control procedure. The spark detection efficiency was estimated to be higher than 97 %, the position resolution was determined to be approximately 0.5 mm. With this system, the characterization of GEM foils can be standardized to a much greater degree than before.

1. Introduction

In the scope of the high luminosity upgrade of the Large Hadron Collider (LHC) several experiments have decided to upgrade their experiments with Gas Electron Multiplier (GEM) [1]. ALICE (A Large Ion Collider Experiment) upgrades the Time Projection Chamber (TPC) [2] with GEM-foils as well as CMS (Compact Muon Solenoid) for the Muon End Cap Chambers [3]. Operation stability is a major requirements for these detectors. The spark detection system was developed within the scope of the ALICE GEM-TPC upgrade [4]. To ensure the performance quality of each GEM-foil, an intensive quality assurance scheme was developed and was strictly followed [5, 6]. An important procedure of this QA scheme is the high voltage (HV) cleaning which is combined with the measurement of the leakage current of the GEM foil. By instantly applying HV with a high current limit to the GEM-foils, sparks are enforced in the foil, which can burn dust or remnants from the manufacturing process. Dust on the foil occurs as a result of transportation or handling of the foils in a not perfectly clean environment. Remnants are caused by shortcomings in the production process of the GEM. A high current limit or even no current limit at all ensures that the sparks have enough energy to fully evaporate the dust and remnants. If the sparks have not enough energy there is the risk that instead of evaporating a permanent connection between the top and bottom layer of the GEM-foil forms thus producing a short.

A frequent appearance of sparks at the same position indicates that there is a defect of the GEM foil at this specific position. Such foils have to be examined with a microscope. The
subsequent leakage current measurement also has the objective to identify potential defects of the GEM foil. In cases where a spark is not triggered by the instantaneous application of the high voltage, defective GEM-foil segments could be identified by an increased leakage current. If the leakage current does not fall below a certain threshold, which was in case of the ALICE GEM-TPC upgrade 500 pA for a segment size of $10 \times 10 \text{ cm}^2$, the foil would not be used. In [4, 5] the importance of environmental boundary conditions for the spark behaviour and the leakage currents have been discussed. The leakage current was measured for each GEM-foil for more than five hours to guarantee the long-term operation stability. After this QA step the GEM-foils were only tested 15 minutes after each production process to guarantee the validity of the processing step. For all of this processes and especially for the long-term leakage current measurement the precise detection of the spark position is important. Therefore an automatic Spark-Detection System (SDS) for GEM-foils was designed, built and characterized.

2. Experimental setup

The idea of the SDS is to substitute the human surveillance by a camera which records the GEM-foil during the HV cleaning and the leakage current measurements. The SDS is therefore a beneficial tool to automatize the QA process. The automation of the spark detection is an important issue if a large quantity of GEM-foils have to be monitored during the production process of a project. An algorithm was developed to analysis the incoming video stream and to identify spark candidates. Due to the small size of the spark and the need to identify also sparks with low intensity, the system has to be operated in a controlled dark environment. A metal box has been build, which decouples the SDS from environmental light changes.

2.1. Hardware design

The SDS (see Figure 1), consists of a large metal housing which has a size of $130 \times 120 \times 75 \text{ cm}^3$. It hosts a polycarbonate box flushed with nitrogen gas in which the foils are placed during the HV cleaning and the leakage current measurements. The gas parameters are monitored with a Rapidox Z3001 device [7]. The HV setup is thoroughly described in [5]. Cutouts at the sides and in front of the box give room for the gas and HV supply lines. The metal housing provides shielding from external disturbances such as human interference. This allows simultaneous current measurements in the pA range. It also guarantees a controlled and reproducible light environment. Illumination inside the metal box is provided by a hand switchable LED bar when needed e.g. camera adjustment. The height of the housing is adjusted such that the camera, mounted on the ceiling of the box, is able to monitor the full active area of a large-size GEM-foil. The camera is a Logitech C310 with a video frame resolution chosen to be $800 \text{ px} \times 600 \text{ px}$. The resulting frame rate is 15 Hz.

2.2. Software implementation

A dynamic linked library (DLL), written in C++ using OpenCV [8] was developed and implemented in LabVIEW [9], which analyzes the video frames and detects discharges by taking the difference between two subsequent frames. Like this, residual light phenomena which are constant in time can be excluded. A frame containing a spark and the resulting difference frame is shown in Figure 2. One can see that all residual light effects are eliminated by the subtraction and just the spark is remaining. A difference frame is further processed if the brightest pixel exceeds a predefined threshold. Spark candidates are then identified by searching for confined spots which have a certain brightness and size. Additionally, the area of the spot should be smaller than 30 px which is derived from observation of spark frames. The detection returns the center of gravity of the detected spots such that subpixel resolution is possible.
Figure 1. Picture of the Spark-Detection System. 1 - Metal box, 2 - Webcam, 3 - LED light, 4 - HV-Box, 5 - Gas analyser, 6 - pA-Meter, 7 - LabVIEW HV software, 8 - Gas connections.

Figure 2. Spark detection in the video material. The left picture shows a frame containing a spark. The right picture shows the difference frame between the left picture and the following frame. Both pictures are color inverted for better visibility. In the difference frame all steady light effects are excluded.

Figure 3 shows that the camera view on the GEM-foil is tilted. This effect occurs as the position of the camera with respect to the GEM-foil can change. As the GEM-foil is put on a drawer which is then connected to the polycarbonate box slight position changes can occur. Comparable coordinate systems can be achieved by a transformation to an orthographic view with defined
Figure 3. The left picture shows the bare camera footage of the GEM. The right picture shows the transformed orthographic view of the GEM. For better position identification the sector outlines as well as sector numbers are added.

scale. For this task, a perspective transformation is used. To calculate the transformation four points in the original view and their coordinates in the orthographic view are needed. The outer edges of the GEM-foil provide the coordinates for the transformation, but require an user input. A transformation matrix from the free image processing library Open Source Computer Vision (OpenCV) is used for the optical transformation. Figure 3 shows the non transformed and transformed frame of an IROC GEM-foil. The transformation is only used to transform detected spark positions into the GEM-foil coordinate system. The spark detection is done in the original frame to save computational resources. The transformed spark position allows to determine if a spark is located inside or outside the GEM-foil area to exclude false detections.

To make the SDS interactive with other QA systems, such as the high voltage program, the functionality is made available in LabVIEW. LabVIEW is capable of executing any external C++ code when it is wrapped into a Windows DLL. To prevent data loss the DLL writes all detected sparks to a file. Furthermore, LabVIEW can query the number of sparks and their positions at all times. The limiting factor for the query frequency is the video frame rate. At 15 Hz the query interval is limited to 67 ms. A reasonable query frequency is at few Hz, but can be scaled depending on the expected spark frequency.

Before the program is started the used geometry and detection threshold needs to be set. Up to now, geometries of a $10 \times 10$ cm$^2$ and the GEM-foils used for the ALICE TPC upgrade (IROC, OROC 1-3) are implemented. An explanation for the naming convention of the GEM foils is given in [2]. Since the video is not stored there is no second detection chance and the threshold needs to be chosen with care. The developed user interface guides the user through the following steps:

- Switch on the internal light and check if the GEM-foil is fully in the video frame.
- Enter the four reference edge points by mouse.
- Validate that the transformation is acceptable.
- Define the file to write the spark data to.
- Switch off the light and start the spark detection.

2.3. Efficiency and position resolution of the SDS

The spark-detection efficiency was evaluated by comparing the discharge candidates to the overcurrent detection of a CAEN DT5521 power supply which had an overcurrent limit of 5 $\mu$A.
The spark detection efficiency was determined to be between 97 % and 99 %. However, the optical Spark-Detection system was able to detect events with multiple sparks in a short time window that could not be detected by the power supply. The position resolution is limited by the camera resolution (1 px ≃ 1 mm) and the reproducibility of the user input for the coordinate transformation. This was tested on a recorded video sequence, which was subject to ten separate analyses, each requiring an independent user input. The resulting aberration of discharge positions indicates that on average the positions are reproducible within a circle of ~ 0.5 mm radius. A detailed description of the systematic concerning the efficiency and the position resolution can be found in [4].

3. Spark detection and results
3.1. Correlation of sparks and defects

![Figure 4. Correlation between a spark and a defect (red data point). The size of the bin does not correspond to the size of the picture.](image)

One important observation made in the course of the quality assurance of the ALICE GEM-TPC upgrade is the fact that an optical inspection is not the sole indicator for the operation stability of the GEM-foil itself. As described in [6] each GEM-foil was optically scanned and the parameters of each hole has been measured. However, it is not conclusive from the optical scan alone if a deformed hole has to be classified as a defect and will be problematic in terms of operation stability later on. A general rule of thumb is that if HV is immediately applied to a GEM-foil, the sparking should disappear after the first one or two minutes. Here it is crucial that the spark position is clearly identified. Figure 4 shows the correlation between a high appearance of sparks (red point) and a defect of the foil. A high voltage of 550 V has been applied. The GEM-foil has been long-term measured for about five hours. In total 97 sparks did occur, but the important fact is the accumulation of four sparks at one specific point. This specific position was examined under an optical microscope. One can see two holes with sharp edges which is a clear defect of the GEM-foil. This GEM-foil was ruled out for the production of chambers. For coming experiments a more time-effective quality assurance could be performed if only GEM-foils which repeatedly sparking at a certain position are optically scanned in detail.

3.2. Impact of holes in the segment boundary

An important topic which was studied during the GEM-foil production for the ALICE TPC upgrade was how to deal with imperfections of the production process. An example of such imperfections can be seen in Figure 5. One can see a hole that enters the segment boundaries
Figure 5. GEM foils with cut holes, that are located on the segment boundary of a GEM-foil. The hole is on copper as well as on the polyimide. Three sparkmaps at three different high voltages are shown. The position of the cut-hole are indicated with a red circle.

between segments and therefore lies partially on the copper and on the polyimide. These holes are called cut-holes. A subdivision of large-size GEM-foils to several segments of an approximate size of 100 cm$^2$ is necessary because one has to keep the capacitance of the GEM-foil at a manageable size. A large capacitance means that more energy is stored in a GEM-foil which is more harmful in case of a discharge. It also has an impact to the noise behaviour as a larger capacitance increases the common mode effect. Shortly after the invention of the GEM-foil, the producers investigated the possibility to first finish the production of the holes in one production step without taking any segment boundaries into account. The segment boundaries as well as the high voltage lines are etched in a later production step. Without taking segment boundaries into account for the hole etching a huge number of holes were always partially on the copper and on the polyimide. These numerous cut-holes introduced a higher spark rate, so that this production method was discarded. Due to the high number of holes which are on the copper and on the polyimide, sharp edges on the copper side were introduced leading to a higher spark rate and therefore to a higher probability to damage the foil. In the present production scheme the masks that contains the holes have to be always aligned with the area for segment boundaries. This makes the production process of the GEM-foil less flexible. During the production of GEM-foils for the ALICE TPC upgrade numerous GEM-foils had a single cut-hole or up to three cut holes. One can see in Figure 5 that although there is a distance of about 400 µm between the holes of two adjacent segments,

1 In this case the segments are comparable to the standard layout of 10 × 10 cm$^2$ GEM foils which is typically the size of small prototypes.
the etched segment boundary has an offset towards the right segments. At first these GEM-foils were discarded. A first study at the production side was not fully conclusive, if such foils have to be discarded because of a higher sparking rate. The study presented in this paper was carried out later with the SDS to be able to better correlate the position of the cut holes and the sparks. For the GEM foils with cut holes, several long-term measurements were performed with increased high voltage settings. In Figure 5 the sparkmaps for three different high voltages (550 V, 555 V and 560 V) are shown. The position of the cut holes are indicated by the red circles. One can see that although numerous sparks appear no increased spark rate could be observed at the cut-hole positions. The spark behaviour of this foil was also tested for a high voltage of 565 V and 570 V. However, no increased sparking was observed either. This indicates that the sparks at lower voltages were coming from dust contamination of the foil. Once the dust was evaporated, the sparking disappeared, although a higher voltage was applied. The high voltage was not increased further than 570 V because the Paschen limit would be reached where continuous discharging begins. In such a case the risk to damage the foil would be very high.

Table 1. Serial number of GEM-foils tested and corresponding number of cut-hole on each foil.

| Serial number GEM-foil | Number of cut-holes |
|------------------------|---------------------|
| I-G1-004               | 2                   |
| I-G1-005               | 3                   |
| I-G1-007               | 3                   |
| I-G2-005               | 1                   |
| I-G4-011               | 1                   |
| O1-G1-005              | 1                   |
| O1-G1-010              | 1                   |
| O1-G4-002              | 1                   |
| O2-G4-008              | 1                   |
| O2-G1-002              | 1*                  |
| O2-G4-001              | 1*                  |
| O2-G4-007              | 1*                  |

Five foils of type IROC, three foils of type OROC 1 and four foils of type OROC 2 which had these cut-holes were tested in long-term measurements of five hours. In total 12 GEM-foils were tested which had in total 17 cut-holes as can be seen in Table 1. The foils marked with a star (*) have a hole which is close to the segment boundary, but still fully in the metal. These foils were originally also classified as cut-hole foils and have therefore been tested with the same procedure. Without these GEM-foils the statistics is reduced to nine GEM-foils and 14 cut-holes. The high voltage was increased as shown in Figure 5. None of them showed an increased sparking behaviour. However, it has to be mentioned that the number of the GEM-foils that has this issue is small. Also the number of cut-holes which have been tested is limited and not comparable to the huge number as in the production scheme quoted in [10]. However, in case of individual cut-holes and even with increased requirements for the high voltage stability an increased sparking rate could not be observed.
4. Conclusion
A spark detection system has been developed to automatically detect and record the time and position of sparks in GEM-foils. The system can be easily adapted for any geometry. The system also should be usable for Micromegas, although it has never been tested so far with this kind of Micro Pattern Gaseous Detector (MPGD). A SDS is an ideal tool to be combined with a high voltage system, that provides high voltage cleaning and current leakage measurements. Measurements showed that sparking hot spots could be precisely identified and, if examined later with a microscope, could be correlated to defects, that were not identified before. It also could be shown, that not all production imperfections will necessarily lead to hot spots as in the case of the cut-hole foils. However, a thorough examination of the spark behaviour under high voltage is advisable to ensure the operation stability of the GEM-foil.

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