Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 13(3), 1686-1695, 2023
Journal of the Institute of Science and Technology, 13(3), 1686-1695, 2023

ISSN: 2146-0574, eISSN: 2536-4618

Fizik / *Physics* **DOI: 10.21597/jist.1295454**

Araştırma Makalesi / *Research Article*

Geliş tarihi / *Received*: 10.05.2023 **Kabul tarihi / *Accepted*: 08.06.2023**

Atıf İçin: Kalkan, Y. (2023). Usage potential of Lignocellulosic material instead of Polyimide in GEM particle detectors. *Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, 13(3), 1686-1695.

To Cite: Kalkan, Y. (2023). Usage potential of Lignocellulosic material instead of Polyimide in GEM particle detectors. *Journal of the Institute of Science and Technology*, 13(3), 1686-1695.

GEM Parçacık Dedektörlerinde Lignoselülozik Malzeme Kullanım Potansiyeli

Yalçın KALKAN*

Öne Çıkanlar:
- Lignoselülozik Gaz Elektron Çoğaltıcı (GEM) yaprakları
- Elektriksel Karakterizasyon
- Çevre Dostu Teknolojiler

Anahtar Kelimeler:
- Lignoselülozik Malzemeler
- GEM dedektörleri
- Elektriksel Karakterizasyon
- Yüksek Enerji Fiziği deneyleri

ÖZET:

Bu çalışma, yüksek enerji fiziği deneylerinde kullanılan Gas Electron Multiplier (GEM) yaprakları için lignoselülozik malzemenin kullanım potansiyelini araştırmaktadır. Saçtırma yöntemi kullanılarak 50 µm kalınlığında bir lignoselülozik film oluşturulmuş ve her iki yüzeyine de 2 µm kalınlığında bakır elektrot tabakası kaplanmıştır. Lignoselülozik malzemenin GEM dedektörlerinde kullanımının uygunluğunu değerlendirmek için elektriksel karakterizasyon çalışmaları yapılmıştır. Ölçümler sırasında tutarlı atmosferik koşulları sağlamak için özel bir odacık tasarlanmış, böylece sıcaklık ve nem değerleri SHT3x sensör modülü ve Rense Sıcaklık/Nemölçer kullanarak zamana bağlı olarak izlenebilmiştir. Elektriksel ölçümler Keithley 4200 yarıiletken karakterizasyon sistemi kullanılarak yapılmış ve farklı atmosferik koşullar altında akımın gerilime bağlı değişimi gösteren I-V diyagramı çizilmiştir. Sonuçlar, lignoselülozik folyo kullanan GEM dedektörlerinin çeşitli yüksek enerjili fizik deneyleri için sürdürülebilir ve verimli dedektörler geliştirme potansiyeli sunduğunu göstermektedir. Çalışma, GEM yapraklarında lignoselülozik malzeme kullanımının avantajları ve dezavantajlarını kapsamlı olarak ortaya koymakta ve GEM dedektörlerinin imalatı için daha çevre dostu alternatiflerin geliştirilmesine katkıda bulunmaktadır.

Usage Potential of Lignocellulosic Material Instead of Polyimide in GEM Particle Detectors

Highlights:
- Lignocellulosic Gas Electron Multiplier (GEM) foils
- Electrical Characterization
- Enviro-friendly Technologies

Keywords:
- Lignocellulosic materials
- Gas Electron Multiplier (GEM) detectors
- Electrical characterization
- High-energy physics experiments

ABSTRACT:

This study investigates the potential use of lignocellulosic material for Gas Electron Multiplier (GEM) foils in high-energy physics experiments. A 50 µm thick lignocellulosic film was created using a scattering method, and both surfaces were coated with a 2 µm thick copper electrode layer. Electrical characterization studies were conducted to assess the suitability of lignocellulosic material in GEM detectors. To ensure consistent atmospheric conditions during measurements, a special chamber was designed to monitor temperature and humidity values over time using an SHT3x sensor module and Rense Temperature/Humidity Meter. Electrical measurements were performed using a Keithley 4200 semiconductor characterization system, and I-V curves showing the current-voltage relationship under different atmospheric conditions were plotted. The results demonstrate the potential for developing sustainable and efficient detectors for various high-energy physics experiments using GEM detectors with lignocellulosic foils. This study comprehensively presents the advantages and disadvantages of using lignocellulosic material in GEM foils and contributes to the development of more environmentally friendly alternatives for GEM detector manufacturing.

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INTRODUCTION

The investigation of the fundamental structure of matter has been a topic of enduring interest, driving scientific inquiry since ancient times. Over the course of history, advancements in technology have significantly contributed to the evolution of our understanding. Initially, matter was classified into the elemental categories of fire, air, water, and earth. However, the discovery of the atom and subsequent identification of numerous subatomic particles using advanced accelerators, colliders, and detectors have vastly complicated our comprehension of matter. Particle detectors play a crucial role in these technological advancements, offering diverse measurement capabilities depending on their design and configuration. Gas detectors, in particular, hold great significance due to their ability to detect radiation rapidly and withstand its effects (Stéphan, 2011). In recent years, remarkable progress has been achieved in the development of gaseous detectors, with extensive research and development projects focusing on photon, charged particle, and neutron detection. While multi-wire and parallel plate gaseous detectors have traditionally been extensively employed in high-energy physics (HEP) experiments, they now face increasing competition from Micro Pattern Gaseous Detectors (MPGDs), which have reached a level of maturity that allows for their widespread application. The utilization of MPGDs has expanded beyond the realm of HEP, finding applications in various other scientific fields, albeit their initial development primarily stems from HEP research initiatives. Notably, the CERN RD51 program and its associated collaborative efforts among multiple research groups worldwide have played a crucial role in unifying these endeavors (CERN RD51 Collaboration).

Polymer materials encompass a critical class of materials with wide-ranging applications, owing to their unique combination of characteristics including mechanical robustness, long lifespan, and chemical inertness (Chen et al., 2016). The exceptional adaptability of polymers arises from their inherent capacity to be tailored for specific applications through manipulation of their chemical architecture and molecular weight (Beginez et al., 2020). Polymeric materials find extensive utilization across diverse industries such as packaging, textiles, construction, automotive, and electronics. In particular, the aerospace industry exploits polymers to fabricate components that exhibit both lightweight properties and high mechanical strength (Patil et al., 2017).

In the automotive sector, the utilization of polymers enables the production of lightweight components, resulting in improved fuel economy through the reduction of overall vehicle weight (Patell et al., 2018). Moreover, there has been extensive exploration of the potential of polymers as biomaterials for various medical applications, including drug delivery, tissue regeneration, and medical implants (Elmowafy et al., 2019). As technological advancements continue to progress, novel polymeric materials are being formulated with enhanced properties and customized for specific applications, thereby further enhancing their significance and utility across diverse industrial sectors (Muhammad, 2021).

Lignocellulosic materials, derived from plant biomass, represent a abundant and sustainable group of substances that find extensive utilization across various industrial sectors (Isikgor & Becer, 2015). The term "lignocellulosic" encompasses the combination of lignin, cellulose, and hemicellulose, which are the primary constituents of plant cell walls (Pang, 2018). These substances possess distinct characteristics, including economic viability, biodegradability, and mechanical robustness, which make them attractive for a wide range of applications, such as biofuel production, paper manufacturing, textile production, and construction materials (Rehman, 2012). Furthermore, lignocellulosic materials have been explored as potential sources of chemicals and pharmaceuticals due to the presence of valuable constituents, including terpenoids, phenolic compounds, and

flavonoids (Butnaru, 2022). With the increasing emphasis on sustainable development, lignocellulosic materials are expected to play a significant role in meeting global energy, materials, and chemical demands, while reducing reliance on non-renewable resources (Cherubini, 2010).

Recent investigations have focused on exploring the electrical properties of lignocellulosic materials derived from plant biomass (Hassan, 2018). The conductivity exhibited by lignocellulosic materials can be attributed to the presence of conductive species, such as metals and carbon, along with ions and water molecules (Markiewicz, 2009). The electrical characteristics of lignocellulosic materials have been extensively studied to evaluate their suitability for a diverse range of applications, including sensors, energy storage devices, and electromagnetic shielding materials (Wang et al., 2021). For instance, research has investigated the feasibility of utilizing lignocellulosic materials as precursors for carbon-based materials in energy storage systems, such as supercapacitors and batteries (Ma et al., 2017). Moreover, investigations have also been conducted to assess the potential of lignocellulosic materials as eco-friendly alternatives to conventional electromagnetic shielding materials, given their low cost and biodegradability (Djafari Petroudy et al., 2023). In recent years, the electrical properties of lignocellulosic materials have received significant research attention, with several studies reporting promising outcomes regarding their application in various electrical fields.

Polymeric materials have emerged as promising candidates for replacing conventional inorganic materials in radiation detection systems, driven by their unique attributes such as enhanced sensitivity, cost-effectiveness, easy processability, and flexibility (Griffith et al., 2020). Radiation detectors based on polymers offer numerous advantages, including reduced background noise and a wide detection range. Various types of polymer materials have been extensively investigated in this context, including organic scintillators, plastic scintillators, and semiconducting polymers (Alberti et al., 2021). Polyvinyltoluene (PVT) is a commonly used plastic scintillator material in radiation detection applications (Sword, 2017). Polyfluorene derivatives have demonstrated excellent energy resolution and high light yield, making them attractive candidates for organic scintillators (Jo et al., 2023). Additionally, conducting polymers such as poly(3,4-ethylenedioxythiophene) (PEDOT) have been explored as potential radiation detectors due to their response to ionizing radiation (Zhang & Yeow, 2020). In our previous study, we investigated the X-ray detection properties of a blend structure of Poly(3-hexylthiophene) (P3HT):Phenyl C61 butyric acid methyl ester (PCBM) with varying PCBM loading ratios (Kalkan et al., 2022). The use of polymer materials in radiation detectors offers several potential advantages over traditional inorganic materials, particularly in terms of cost and flexibility, making it a highly active area of research in recent years.

The Gas Electron Multiplier (GEM) has emerged as a prominent gas detector in numerous particle physics experiments conducted at the Large Hadron Collider (LHC) of CERN, garnering significant attention. Originally conceived by Fabio Sauli as a pre-amplifier, the GEM technology has demonstrated its versatility by finding diverse applications in fields such as fire alarm systems, medical diagnostics, astrophysics, and biology. Notably, GEM structures have transcended their initial role as mere pre-amplifiers to become independent and self-contained detectors. A GEM detector comprises a polymer foil with metal coatings on both sides, featuring a high density of microscopic holes (Sauli, 1996). By applying suitable potentials, the GEM operates as an efficient electron pre-amplifier for gas-ionizing radiation, facilitating the transfer of a substantial portion of the amplified electron charge to either a pickup electrode or another amplification device (Bachmann et al., 1999). When ionizing particles traverse the GEM foil, they induce gas ionization within the surrounding volume, resulting in the formation of an electron and ion cloud. The electrons migrate towards the holes in the GEM foil, passing through them and generating a cascade of secondary electrons.

Subsequently, these secondary electrons are accelerated by a high voltage applied across the GEM foil, triggering an avalanche effect and leading to the accumulation of electrons on a readout plane positioned behind the GEM. The signal produced by a GEM detector typically manifests as a current pulse proportional to the number of electrons collected on the readout plane. The magnitude and shape of this pulse can be utilized to deduce the energy and trajectory of the ionizing particle responsible for the initial ionization event. Overall, the GEM detector represents a highly sensitive instrument capable of particle detection.

The standard GEM detector configuration employs poly(pyromellitic dianhydride-co-4,4′-oxydianiline) (PMDA/ODA) Polyimide (PI) material as the GEM foil. However, certain investigations have unveiled a phenomenon in which a fraction of electrons passing through the GEM aperture interact with the PI substrate, leading to the generation of water molecules within the polymer chains (Kalkan, 2012). This phenomenon results in a reduction in the amplification gain of the gaseous amplification mechanism due to electron loss, possibly influenced by the electron affinity of the PI (Varun, 1999; Kafafi, 1990). Additionally, the presence of water molecules within the polymer matrix modifies the conductivity of the GEM foil, posing challenges for the calibration and simulation of the detector. To tackle these challenges, researchers have pursued the identification of alternative substrate materials to replace polyimide in the construction of GEM detectors (Fujiwara, 2014; Chernyshova, 2019; Franchino, 2016).

This research article introduces an innovative methodology for the production of GEM foils by employing lignocellulosic material as an alternative to polyimide. The study primarily focuses on the comprehensive electrical characterization of the newly developed foil and investigates its potential for integration into GEM detectors. By conducting a meticulous analysis of the merits and limitations associated with lignocellulosic material as a substrate, this article assesses the viability of its implementation in the construction of GEM detectors.

MATERIALS AND METHODS

In this study, a 50 μm thick film derived from lignocellulosic material was synthesized and coated with a 2 μm thick layer of copper electrodes on both surfaces utilizing the sputtering technique. To mitigate any potential adverse thermal effects on the film, the deposition process was conducted at a lower energy density and slower rate. This resulted in a configuration that allowed for the utilization of both sides of the lignocellulosic substrate as functional electrodes, thereby significantly enhancing the overall performance and efficiency of the GEM detector. Figure 1 presents a schematic diagram illustrating the sandwich-like structure formed by the copper electrodes, providing a visual representation of the layering arrangement within the GEM detector.

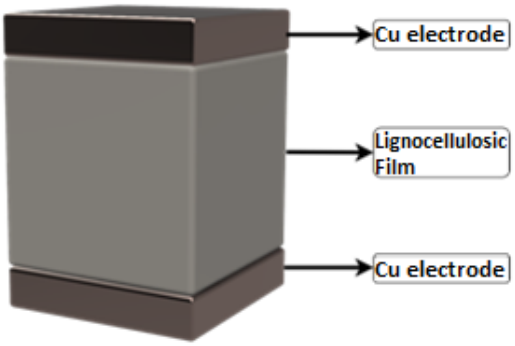

Figure 1. Schematic view of lignocellulosic film coated with copper electrodes

For conducting electrical measurements, a printed circuit board (PCB) with designated contact points corresponding to the copper electrodes of the GEM sheet was utilized. To ensure consistent atmospheric conditions and prevent their influence on the detector's performance and the electronic properties of the insulating layer on the lignocellulosic film, a custom-designed chamber with adjustable atmospheric conditions was constructed. This chamber design was created using parametric design software and a three-dimensional printer, incorporating three inlets for gas inlet, gas outlet, and chamber vacuuming, as well as a socket input for electrical analysis. To ensure the gas-tight integrity of the chamber during experiments, a rubber gasket was inserted between the cover and the case. Figure 2 presents a photograph of the fabricated chamber.

Figure 2. Photograph of the chamber

During the electrical characterization, the chamber's temperature and humidity conditions were monitored using an SHT3x sensor module. The collected sensor data throughout the measurement process was transferred to a personal computer via a serial communication protocol for storage. Moreover, the physical conditions of the laboratory were monitored using an external temperature and humidity meter (Rense Temperature/Hygrometer). The Keithley 4200 semiconductor characterization system was utilized to conduct the electrical measurements while varying the humidity and temperature. Current variations were observed by applying voltage at different voltage steps within the range of -50 V to +50 V. The electrical characterization procedures were carried out at room temperature, under vacuum conditions, and in the presence of high purity Argon gas. The copper-clad lignocellulosic film PCB was positioned between the contacts formed by circuit boards for the electrical characterization, and the wires connected to the contacts were soldered to the socket on the switchgear. The SMU1 and SMU2 terminals of the Keithley 4200 device were connected to the other end of the socket to establish the electrical measurement setup. Figure 3 presents an illustration of the experimental configuration.

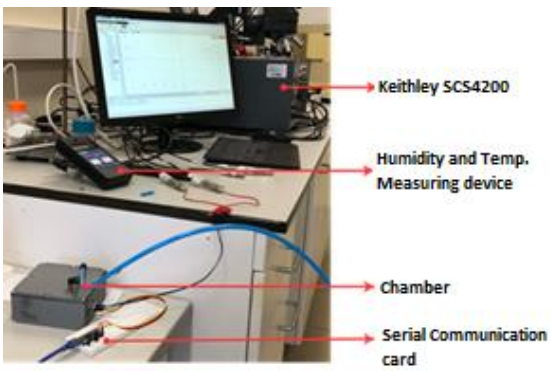

Figure 3. Photograph of the electrical characterization setup

During the measurements, the influence of voltage step increments on the characterization was investigated, with preferred voltage increments of 0.05V, 0.1V, and 0.2V. Subsequently, a vacuum

environment was established using a mechanical pump, and electrical measurements were carried out under vacuum conditions. After the completion of the vacuum measurements, the measurements were repeated in the presence of high purity Argon gas.

RESULTS AND DISCUSSION

Figure 4 presents the temporal evolution of temperature and humidity values inside the measurement chamber throughout the characterization processes. The plot displays the changes in temperature and humidity over time during the measurement procedures. The x-axis represents time in seconds, while the left y-axis corresponds to the humidity level inside the chamber. Conversely, the right y-axis denotes the temperature variation within the cell. The red curve represents the humidity change, while the blue curve illustrates the temperature variation. The graph clearly demonstrates a significant decrease in humidity level within the cell, approaching nearly zero, particularly upon the introduction of high purity argon gas.

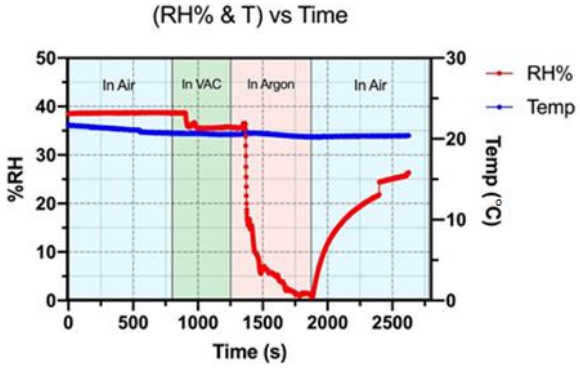

Figure 4. The plot of change of temperature and humidity in the chamber over the time

The I-V curve depicting variations in current as a function of voltage under distinct atmospheric conditions has been illustrated in Figure 5. Upon comparison of the acquired results with the outcomes reported in the existing literature concerning Polyimide, it can be asserted that while Lignocellulosic-GEM sheets exhibit lower electrical resistance compared to Polyimide-GEM sheets, they still fall within the acceptable resistance threshold suitable for application in GEM detectors (Sessler, 1986).

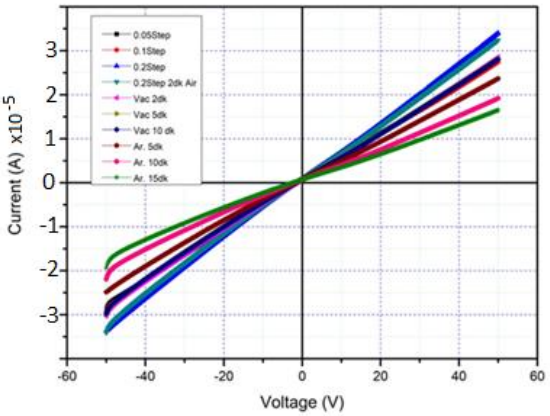

Figure 5. I-V diagram

The x-axis of the presented graph represents the applied voltage, while the y-axis corresponds to the measured current values. To investigate the influence of varying atmospheric conditions, a delay period was introduced between the electrical measurements. The results demonstrate the overlay of I-V curves obtained under room conditions, whereas a reduction in current values was observed after

exposure to a vacuum environment and introduction of high purity argon gas. Despite the nearly negligible humidity level during the measurements, the current value at a voltage of +50V exhibited a decline from 3.5 µA to 1.5 µA. To further elucidate the impact of humidity on electrical properties, the resistance values under different conditions were depicted graphically in Figure 6.

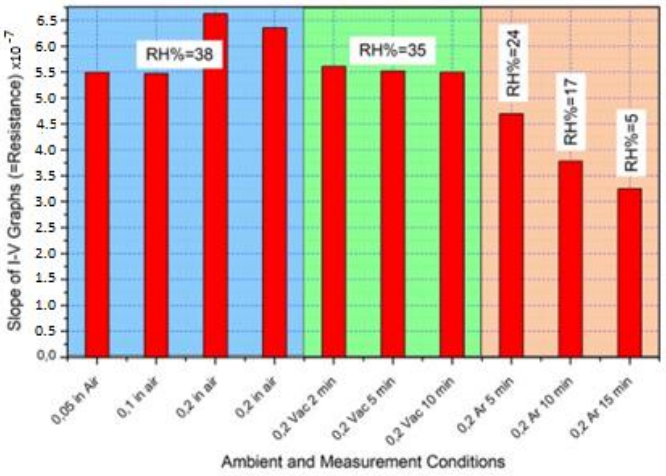

Figure 6. Values of the slope of the I-V diagram under different conditions

Under ambient conditions in air, a series of incremental potential differences ranging from 10 to 50 Volts were applied to lignocellulosic films. This process resulted in the acquisition of a time-dependent plot illustrating the variation of current in Figure 7. The obtained results are congruent with the outcomes attained by Franchino through the utilization of Diamond-GEM (Franchino, 2016).

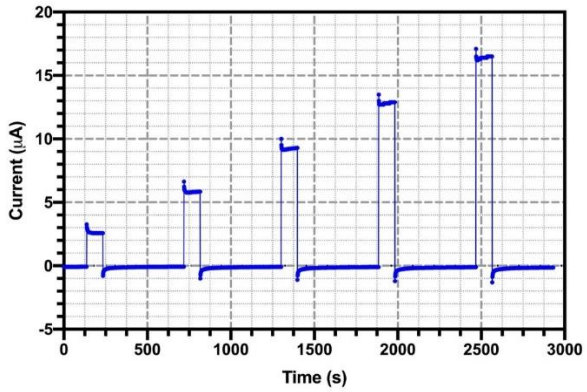

Figure 7. The time-dependent plot illustrates the variation in current observed on a thick lignocellulosic film upon the application of potential differences within the range of 10-50 Volts

Upon careful analysis of the acquired graph, a remarkable observation was made concerning the unexpectedly elevated current values. This phenomenon was attributed to the infiltration of copper atoms into the cellulose film during the coating process utilizing a spraying-based technique. The penetration of copper atoms into the film resulted in a notable reduction in the inter-electrode distance at specific locations. Consequently, this proximity between the surface electrode layers led to an enhancement in the overall conductivity of the structure.

The charging-up plot of the lignocellulosic film was obtained under a voltage of 10 Volts and is presented in Figure 8. Remarkably, the electrical charging behavior exhibited by the film deviated from the expected logarithmic pattern and instead followed an inverse square law. Ongoing research endeavors are focused on precisely fitting a mathematical curve to the graph, enabling a comprehensive mathematical analysis of the observed charging behavior.

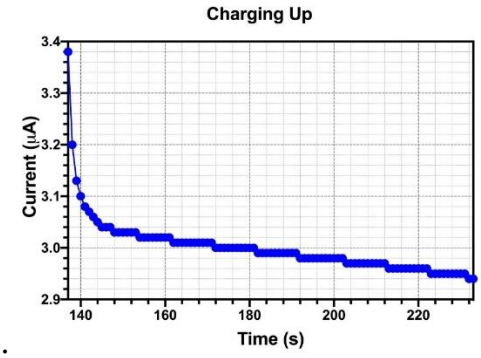

Figure 8. The plot of loading of lignocellulosic film under applied 10 Volts

The discharging plot of the cellulosic film, following the abrupt cessation of a 10 Volt voltage application, is presented in Figure 9. This graph illustrates the behavior of the film as it undergoes the process of discharging after the voltage is instantaneously removed.

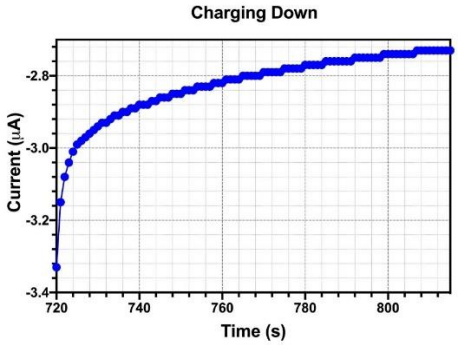

Figure 9. The plot of discharging of lignocellulosic film

In order to examine the polarization effect of the lignocellulosic film, a series of reverse voltages ranging from 10 to 50 Volts were incrementally applied, as illustrated in Figure 10. Analysis of the obtained data indicated that the polarization effect was not pronounced in the structure demonstrating ohmic behavior. Additionally, the response delays to the reverse voltages were observed to be within reasonable levels.

Upon juxtaposing the attained results with the I-V characteristics derived from the extant literature for ultra-thin Polyimide films, it becomes evident that the thickness of the film emerges as a highly influential parameter impacting the charging and discharging durations on the foil (Iwamoto, 1992).

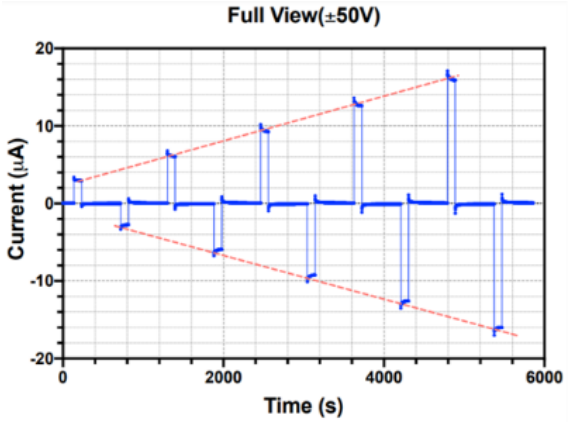

Figure 10. Time dependent variation of the current on the lignocellulosic film under reverse potential differences in the range of 10-50 Volts

Upon analyzing the charging and discharging characteristics of the lignocellulosic GEM foil under tension, it was observed that the time constants closely resembled those observed for the polyimide material. Furthermore, the examination of the obtained results revealed that the resistance value of the film was in the range of 10^{10} Ω, which aligns with the anticipated and reasonable range for a film intended for use in the GEM detector sheet.

CONCLUSION

This innovative technology presents significant potential for the development of cost-effective and environmentally friendly detectors in high-energy particle physics applications. The experimental results obtained from the conducted studies demonstrate the favorable electrical properties of lignocellulosic films, including high resistivity and low background noise, rendering them suitable for implementation in GEM detectors. However, further research is warranted to optimize the manufacturing process and enhance the film's performance characteristics, such as charge gain and energy resolution. In conclusion, lignocellulosic GEM detectors offer a promising pathway for the advancement of sustainable and efficient detectors in diverse high-energy physics experiments.

ACKNOWLEDGEMENTS

This study was supported by Turkish Energy, Nuclear and Mineral Research Agency. Project number:2020 TENMAK(CERN)A5.H1.F5-27]

Conflict of Interest

The article author declare that there is no conflict of interest.

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