Charged particle detector-related activities of the KACST radiation detector laboratory

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Introduction

New radiation detection technologies have emerged, increasing the number of technologies that could be utilized in large-scale applications, such as in medical imaging, material imaging, and sensors in digital cameras (Klyachko et al., 2011). A country such as Saudi Arabia, which is interested in developing its technological base, must promote developments in a basic detector and sensor physics in its universities and research centers. In support of Saudi Arabia’s strategies for advancing science and technology, the King Abdulaziz City for Science and Technology (KACST), the country’s leading research organization, launched a project in mid-2009 involving the establishment of the first radiation detector laboratory in the country. This project aims to design, develop, and operate several multi-purpose radiation detectors and collect the largest amount of data that are useful in conducting applied scientific studies. Moreover, it aims to establish collaborations with international institutions to facilitate the transfer of technological knowledge to Saudi scientists, leading to the participation of Saudi scientists in international experiments and collaborations in the field of modern detector technology (Alghamdi et al., 2013).

The detector laboratory is located in the western side of the KACST main campus, and it was built according to the international standards. The laboratory was designed as stand-alone and was planned taking into consideration the areas where it can offer support and services. The laboratory was initially installed with the basic equipment, but it has a sufficiently large space to easily accommodate more sophisticated detectors and detector arrays (Figure 1a). The laboratory is equipped with all types of modern instruments for radiation detection, devices for data acquisition, and facilities for mounting, testing, and calibration of small and medium radiation detectors. The instruments referred to above include sensor test equipment, analogue analog and digital signal processing electronics, a gas system, a clean room, and a mechanical workshop (Figure 1b), among others (Alghamdi et al., 2013). Several radiation detectors in this laboratory were designed, tested, and developed by the KACST-based researchers, and some were developed through their collaboration with international institutes. The following sections briefly describe the detectors developed thus far.

1. Gas Electron Multiplier (GEM) detector

The GEM detector was invented by Fabio Sauli at the CERN laboratories in 1997 (Sauli, 1997). The use of a GEM detector is one of the most important techniques in radiation detection (Martinengo et al., 2009). The basic principle of this device involves the multiplication of electrons resulting from the gas ionization inside an ionization chamber via the GEM layers, and these phenomena are triggered by a falling radiation (Sauli, 2001). This type of detector is widely used in high-energy physics because of its superior ability to determine with high accuracy the location of ionization caused by charged particles (e.g., Altunbas et al., 2002; Bachmann et al., 2001; Ketzer et al., 2001). A typical GEM detector consists of a GEM foil, a readout...
board, frames, a window, the body of the detector, a signal processor, a gas system, and a high-voltage (HV) supplier.

The design of the detector built by the KACST-based researchers is similar to those developed by other investigators (e.g., Martinengo et al., 2009; Sauli, 2001). Apart from the readout unit, PCB board, and GEM foil, the rest of the materials making up the detectors described herein were either locally provided or were fabricated by the researchers themselves. All processes related to detector building were carried out by the KACST-based researchers after attending several training programs and workshops in international institutions, such as in GSI in Germany and CERN in Switzerland. Two versions of the GEM detectors were developed, as discussed below.

1.1 KACST’s first prototype of GEM detector

For this detector, a single 10 cm × 10 cm GEM foil of the standard geometry (50/70 µm whole diameter) was used. The center-to-center distance between the holes is 140 µm, and the readout board made of epoxy and Kapton material has a 23 cm × 23 cm dimensions. The induction/anode electrode is a Cu micromesh deposited on a G-10 board. The detector’s frame was made of epoxy material, whereas the window was made of Kapton. The GEM detector was filled with a mixture of Ar and CO₂ at an 80:20 ratio through the supporting gas system. HV was applied using the HV supplier and was regulated by using the electronic circuits designed in our laboratory. The signals from the detector were fed to a preamplifier and then to an amplifier; the amplified signals were then sent to a pulse analyzer. Figure 2a shows the first GEM detector developed in our laboratory (Maghrabi et al., 2015, Al Ghamdi and Maghrabi, 2014). Several calibration procedures and experimental tests using different mixtures of gases and different radioactive sources have been carried out to test the performance of this detector. Figure 2a shows a sample of the spectrum obtained by the developed GEM detectors after a two-hour exposure to the ²⁴¹Am source; the spectrum consists of one γ peak and two α peaks. The two α peaks are clearly seen in the spectrum, and this finding is comparable with that obtained by other investigators, although although the shape and strength of the obtained spectrum are slightly different.

1.2 KACST-modified triple GEM detector

Although the first prototype of the GEM provides acceptable results, this model requires some modifications to achieve optimized functionality and performances and thus become suitable for advanced applications. The researchers designed the new system through their collaboration with the Medical Physics Department of

Figure 1. Photographs showing (a) a workspace in the KACST detector laboratory and (b) an on-going work and some of the detectors built in the laboratory.

Figure 2. (a) The first model of the single GEM detector fabricated in the KACST detector laboratory. (b) ²⁴¹Am source spectrum as obtained by the developed GEM detector.
the King Faisal Specialized Hospital and Research Center. The new detector consists of three GEM foils (10 cm × 10 cm each) with a conductive housing made of aluminum material; it also includes a stainless steel frame, which is the replacement of the aluminum frame. The advantage of the new housing is that it allows one to easily deal with the detector’s interior. Between each layer is a rubber O ring that prevents gas leaks. Six HV inputs and six readout units were added, and the window is made of a Kapton–aluminum sheet (Alghamdi et al., 2014; Maghrabi et al., 2015). Figure 3 shows the final version of the triple GEMtriple-GEM detector developed at the KACST.

The performances of the developed triple GEMtriple-GEM detector were determined by conducting two experiments. The first experiment tested its ability to identify a spectrum of a radioactive source. The second experiment examined the capability of the detector to produce a two-dimensional image of different sources. For these purposes, an x-ray source was used.

All of the experimental setups were placed inside a 10-mm-thick iron box to ensure safety during the x-ray (Figure 4).

For the first experiment, the $^{137}\text{Cs}$ source was used. Figure 5 shows the spectra for the $^{137}\text{Cs}$ source and the cosmic rays. A well-resolved and clearly distinguished peaks were observed.

Figure 6 shows a two-dimensional image of the $^{90}\text{Sr}$ source taken using an x-ray source and recorded by the newly developed GEM detector. The results of both experiments demonstrated the excellent performance of the detector and the possibility of its development for future uses, including medical imaging. The new GEM detector is currently available for student projects and teaching purposes. Research activities are in place to develop the capabilities of the new GEM detector for medical applications and cosmic raycosmic-ray observations.

2. Multi-wire detectors

A multi-wire proportional chamber (MWPC) is a type of any type of gaseous detector known for its position resolution accuracy and is used in high-energy experiments due to its high counting rate capabilities (e.g., Blum & Rolandi, 1993; Charpak et al., 1968; Sauli, 1977; Varga et al., 2013). A three-layer MWPC detector (40 cm × 40 cm) was developed in our laboratory for continuous monitoring of high-energy cosmic raycosmic-ray muons (Figure 7).

The detector consists of an array of thin, parallel, and equally spaced wires. This telescope was designed to consist of three layers of 40 cm × 40 cm MWPC that are stacked on top of one another and powered by an HV supplier. Each layer consists of an array of 16 anodes (12 microns) and 16 field wires (24 microns). The output signals from the detector are pre-amplified using a custom-made preamplifier circuit. A discriminator unit was used to select the amplified signals against the background noise. A Raspberry Pi computer card (Varga et al., 2013) receives the signals from both the preamplifier and discriminator chips through the MtRD Board data acquisition card (e.g., Oláh et al., 2015). A dedicated dedicated software was developed to interface with the electronics to record and store data in 1 ms resolution. While this type of detector has been primarily developed and used for high-energy experiments, our detector has been used for continuous monitoring of high-energy CR, making the long-term observations obtained using our detector the first of its kind worldwide (Maghrabi, AlAnazi, Aldosari, Almuteri et al., 2017a, 2017b).
3. Multi-Wire tracking system for muon tomography

Muon tomography is an imaging technique that utilizes cosmic ray cosmic-ray muons to generate three-dimensional images and to draw a density profile of an object of interest. Cosmic ray Cosmic-ray muons have higher energy and smaller cross section cross-section compared with the conventional x-ray, making them more deeply penetrating and suitable to be used to explore different geological structures and to obtain images through much thicker materials (e.g., Alvarez et al., 1970; Ambrosino et al., 2015; Bonechi et al., 2015; Saracino & Carlóganu, 2012).

Using the multi-wire technology, we developed a three-dimensional tracking detector in collaboration with the Wigner Institute in Hungary (Oláh et al., 2015, 2012, 2013). The detector has a dimension of 51 cm × 46 cm × 32 cm and is contained in a plexiglass box filled with the exhaust chamber gas. The box isolates the detector from the environmental environment as well as mechanically supports the detector (Figure 9).

The detector consists of four sensitive MWPC layers; each layer has been constructed with segmented with 21 μm sense (anode) wires and 100 μm field-shaping wires. Perpendicular to the wires, the lower cathode is segmented into 4 -mm-wide strips (pads). A PIC32 microcontroller system is used to control the operation of the detector. The individual field wires and pad signals are amplified, discriminated, processed, and stored for further analyses (Oláh et al., 2012). A dedicated dedicated software was developed, allowing the user to determine the position and direction of particles and to exclude noisy signals. Also, the software has the capability to plot the rates of incident particles and to test the response of each track of the detector during an experiment. Moreover, users can test the functionality of the detector by plotting the efficiency of the field wires and pads individually.

Several experiments have been conducted to test the performance of the muon tomographer. Figure 10 shows the results of an experiment carried out by placing the detector for about one week at the basement of a tower under construction at the KACST. The efficiency plots for each layer of the detector indicated stable performances during the course of the experiment. The generated image of the materials detected by the detector reveals the structure of parts of the building found above the detector.

The results obtained from the developed system are thus far acceptable. However, more exploration studies involving the use of muon tomography in various applications are recommended. These studies include monitoring geological places, such as caves in mountains, which can be found across the country. In addition, a research plan that is already in place aims to develop a scintillator material-based muon...
tomography system that could collect the largest amount of CR muons.

4. CARPET system for charged particle monitoring

A CARPET detector was developed in collaboration with the Lebedev Institute in Russia. This detector is used to detect and monitor the low-energy secondary component of CRs produced by primary galactic cosmic rays, solar cosmic rays, and charged particles from the Earth's atmosphere; examples of such particles are those produced by environmental processes (dust storms and thunderstorms) at different time...

Figure 6. The left panel shows the experimental setup. The right panel shows the two-dimensional image of the $^{90}$Sr source taken using the x-ray source.

Figure 7. Setup for the MWPC detector developed at the KACST detector laboratory.
scales. The detector is based on a large number of Geiger–Muller detectors arranged in a matrix in order to observe different particles with different energies.

The CARPET detector consists of two layers (upper and lower) of Geiger counters (STS-6) enclosed in a light-tight box and attached to a platform of approximately 1.5 m × 1.5 m. Each layer contains 60 Geiger counters, and the layers are separated by a 0.7 -cm-thick aluminum layer that absorbs low-energy particles, such as electrons (Figure 11). The operation of the detector is controlled by an interface unit that consists of all the required electronic circuits (Maghrabi et al., 2020).

The signals from the counters are converted into standard TTL pulses and counted by the counter at the interface unit. The electronics unit of the detector records data regarding the particles that cross the upper or lower layers individually and those that cross the upper and lower layers at the same time (coincidence), and this unit is called a telescope (Morzabaev et al., 2018). Theoretical simulations indicated that the lower and upper layers are both sensitive to electrons and positrons with energies higher than 200 keV, to protons with energies above 5 MeV, and to muons with energies higher than 1.5 MeV. However, it was established that the telescope channel could detect electrons with energies greater than 5 MeV, protons with energies greater than 30 MeV, and muons with energies greater than 20 MeV (e.g., De Mendonça et al., 2011).

Figure 12 shows the count rate of the charged particles recorded by the three-channel CARPET during a thunderstorm event that occurred on December 14–15, 2018. The data obtained from the electric field (EM 100) were used to analyze this event. A correlation was observed between the increase in charged particles as recorded by the lower and upper channels and the electric field. By contrast, the telescope data show no significant variations, indicating that high-energy particles were not produced during the said event.

5. Single charged particle detector

This detector was initially developed by the Lebedev Institute and later modified by our group. The detector consists of two units of Geiger counters (STS-6 type) placed on top of each other and separated by a 7 -mm-thick aluminum layer; it records the data obtained by the single counter and those simultaneously obtained by both counters (telescope) (Figure 13). The electronics unit of the detector consists of several electronic circuits that were locally made. This detector was mainly designed for mobile studies and is used for charged particle measurements from ground sources (telecommunications and/or electricity towers) and at high altitudes. It is equipped with temperature and pressure sensors and an SD memory card for data recording and storage.
Figure 10. (a) Experimental setup used to test the muon tomographer (inset) placed inside the KACST tower, (b) shows the rate the detected particles for all the tracks, (c) indicates the efficiency of the track no. 32 in the detector, and (d) shows the final 2-D image obtained by the detector.

Figure 11. The CARPET detector.
This detector has been used in civilian aircrafts in several local flights. In all of these flights, the detector was placed in the same position on the aircraft.

Figure 14.a shows that the flight route on October 30, 2019, is from Riyadh (24.71° N, 46.67° E) to Jeddah (21.48° N, 39.19° E). The variation in the charged particles (single counter and telescope) from the ground back to the ground is illustrated in Figure 14 (b and c). It can be seen that the number of charged particles increases as the altitude increases. At the cruising altitude, the charged particles remained

Figure 12. Data obtained by the three-channel CARPET during a dust storm event that occurred on December 14–15, 2018. The electric field data are also presented.
stable and varied slightly according to the atmospheric conditions at that altitude.

6. Scintillator detectors

6.1 Single-channel detector

Scintillator detectors are among the oldest devices used for charged particle detection. They are characterized by their large collecting area and long-term stabilities. The first charged particle detector installed in Saudi Arabia in 2002 was a scintillator detector (Maghrabi et al., 2012). Since that time, the detector has been utilized to record high-energy cosmic ray cosmic-ray muons. Several research papers have been published using the data obtained by this detector (e.g., Maghrabi & Al Mutairi, 2018).

The detector is a single 1,000 mm × 1,000 mm × 50 mm sheet of plastic scintillator viewed by a photomultiplier tube (PMT) with 120 mm diameter. The signals from the PMT are pre-amplified, amplified, and discriminated against the background using fabricated electronic circuits. The selected signals are digitized by a homemade A/D converter and then linked to a PC card (Figure 15).

In late 2015, as part of the activities of our laboratory, this detection system was upgraded in terms of its electronics and its software. A dedicated software was developed for logging of data, interfacing with electronics, display of results, and storage of data (Maghrabi, Al Ghamdi et al., 2014). Figure 16 shows the time series of the CR muons detected by the upgraded scintillator detector from March 2016 to October 2019. The detector demonstrated stable performances wherein the seasonal variations of the CR muons are clearly evident.

6.2 Rotatable KACST muon detector

The principles and components of this detector are similar to those of the single channel detector, but two sheets of plastic scintillators are placed on top of each other and operated in coincidence inside a rotatable box (Alghamdi et al., 2014; Maghrabi et al., 2014). The detector can be moved around the horizontal axis; hence, the variations of the cosmic rays (muons) at different angles can be measured and studied (Figure 17a).

Figure 17b shows the zenith angle variations recorded by the detector over a course of over several days for each angle.

7. Mini neutron monitor

Neutron monitors (NMs) are among the oldest types of detectors used to monitor the low-energy neutron component of cosmic rays. Several NMs are distributed worldwide, and their data are available for space weather studies (Stoker, 2009).

In order to contribute to the data gathered by the NM monitors installed worldwide, and taking advantage of the uniqueness of the location of Saudi Arabia, we conceived the idea of installing an NM in our country. Additionally, this type of detector will complement the existing CR detectors in our laboratory. One of the drawbacks of NMs is their large size and heavy weight. However, a new generation of small NMs has been developed, one of which is installed in our country (Heber et al., 2014; Krüger et al., 2003; Poluianov et al., 2015). This detector was developed in collaboration with the University of South Hamton in South Africa (Krüger et al., 2003). The detector is approximately 85 cm in length and approximately 60 cm in diameter (Figure 18).

While this detector is small in size, its performances and capabilities of recording CR neutrons are similar to those of the large conventional NMs (Heber et al., 2014; Poluianov et al., 2015). The counter (LND2043 type) of this detector is approximately 63 cm long and is filled with BF3 gas at a pressure of approximately 933 mbar. A PIC32-type controller is used to control the detector’s operation, which includes HV supply and signal amplification, discrimination, and processing (Poluianov et al., 2015). The mini NM was installed in June 2018, and it was in operation until mid-2019 (Maghrabi et al., 2019). The performances of the detector during this period were not stable due to technical problems in the control unit. However, a new control unit was installed by late 2019; since then, the detector’s performance has been stable. Figure 19 shows an example of the diurnal variations of the CR neutrons within a six-month period. The daily pattern of the NM data is characterized by a maximum intensity that occurs around 13 h UT, corresponding to 15 h LT; these results are comparable with those obtained by Mailyan and Chilingarian (2010).
Figure 14. (a) Flight route on October 30 2019 from Riyadh to Jeddah (https://www.flightradar24.com) (b) CR measured by the single-counter, and (c) by the telescope channel. The altitudes are indicated.
Figure 15. Schematic diagram showing the main components of the scintillator detector.

Figure 16. Time series of the CR muons detected by the upgraded scintillator detector from March 2016 to October 2019.

Figure 17. (a) Photograph of the CR rotatable telescope. (b) Variations in zenith angle as determined by the rotatable telescope.
Conclusions

In 2009, KACST, the country’s leading research organization, launched a project to establish the first radiation detector laboratory in Saudi Arabia. This project aims to design, develop, and operate several multi-purpose radiation detectors for scientific studies. The laboratory was well-built, taking into account the future developments in radiation detection and was installed with all the necessary equipment and instrumentation. Several accomplishments have been achieved, as follows:

- Four charged particle detectors were designed and developed in collaboration with international institutions. These detectors are the Muon Tracking Detector (in collaboration with the Wigner Institute in Hungary), CARPET and Single-Channel Small Detectors (in collaboration with the Lebedev Institute in Russia), and the Mini NM (in collaboration with the University of South Hamthon in South Africa). Also, the researchers have been involved in several training programs, workshops, and experimental works in the above-mentioned institutions during the course of designing and building the said detectors. Their involvement in these projects has led them to acquire great knowledge and experience. Some of the primary data obtained by these detectors were analyzed and reported, and they indeed showed good results.
- Four detectors were built by the research group themselves, namely, the first and the modified versions of the GEM detectors, the upgraded version of the muon detector, a rotatable muon telescope, and an MWPC detector.
- Several graduation projects for university students outreach training for school students, and training courses for other organizations were carried out using the laboratory facilities and detectors.
- A reasonable amount of data has been collected by these detectors; the use of these data, which are available for future studies, is advantageous given the unique location of Saudi Arabia.

Figure 18. Mini NM installed at the KACST.

Figure 19. Diurnal variation in the NM data as observed by the KACST’s mini NM from January 2020 to July 2020.
• Some of the results obtained by the detectors have been discussed and presented. The obtained results have shown excellent and compatible performances.

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No potential conflict of interest was reported by the authors.

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