Nuclear Inst. and Methods in Physics Research, A 954 (2020) 161231

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Operation and performance of microhexcavity pixel detector in gas discharge and avalanche mode

A. Mulski [a], Y. Benhammou [c], J.W. Chapman [a], A. Das [c], E. Etzion [c], C. Ferretti [a], P.S. Friedman [b], R.P. Johnson [d], D.S. Levin [a,*], N. Kamp [a], H. Ochoa [a], M. Raviv-Moshe [c], N. Ristow [a]

[a] Department of Physics, University of Michigan, Ann Arbor, MI, 48109, United States
[b] Integrated Sensors, LLC, 2403 Evergreen Rd., Ottawa Hills, OH, 43606, United States
[c] School of Physics and Astronomy, Tel Aviv University, Tel Aviv, 69978, Israel
[d] Department of Physics, University of California Santa Cruz, Santa Cruz, CA, 95064, United States

ARTICLE INFO

Keywords:
Gas based radiation detectors
Pixel detectors
Particle detectors

ABSTRACT

The Microhexcavity Panel (μHex) is a novel gaseous micropattern particle detector comprised of a dense array of close-packed hexagonal pixels, each operating as an independent detection unit for ionizing radiation. It is a second generation detector derived from plasma panel detectors and microcavity detectors. The μHex is under development to be deployed as a scalable, fast timing (ns) and hermetically sealed gaseous tracking detector with high rate ($> 100\,\mathrm{KHz/cm^2}$) capability. The devices reported here were fabricated as 16×16 pixel arrays of 2 mm edge-to-edge, 1 mm deep hexagonal cells embedded in a thin, 1.4 mm glass–ceramic wafer. Cell walls are metalized cathodes, connected to high voltage bus lines through conductive vias. Anodes are small, 457 μm diameter metal discs screen printed on the upper substrate. The detectors are filled with an operating gas to near 1 atm and then closed with a shut-off valve. They have been operated in both avalanche mode and gas discharge devices, producing mV to volt level signals with about 1 to 3 ns rise times. Operation in discharge mode is enabled by high impedance quench resistors on the high voltage bus at each pixel site. Results indicate that each individual pixel behaves as an isolated detection unit with high single pixel intrinsic efficiency to both βs from radioactive sources and to cosmic ray muons. Continuous avalanche mode operation over several days at hit rates over $300\,\mathrm{KHz/cm^2}$ with no gas flow have been observed. Measurements of pixel isolation, timing response, efficiency, hit rate and rate stability are reported.

Contents

1. Introduction

The Microhexcavity Panel (μHex) is a novel, gaseous micropattern particle detector comprised of a dense array of close-packed hexagonal pixels, each operating as an independent detection unit for ionizing radiation. The μHex is under development as a scalable, fast timing (ns) and ultimately, sealed gas-hermetic tracking detector with high rate (>100 kHz/cm^2) capability. Derived from the earlier plasma panel detector [1] and microcavity detectors [2], they are fabricated as 16×16 pixel arrays of 2 mm edge-to-edge, 1 mm deep hexagonal cells embedded in a thin 1.4 mm glass–ceramic substrate. Cover plates

* Corresponding author.
E-mail address: dslevin@umich.edu (D.S. Levin).

https://doi.org/10.1016/j.nima.2018.09.066
Received 24 July 2018; Received in revised form 31 July 2018; Accepted 14 September 2018
Available online 22 September 2018

can be glass or glass–ceramic, 300 μm thick. Pixel walls are metalized cathodes, connected to high voltage bus lines through conductive vias. Anodes are small, thick-film discs (457 μm diameter) screen printed on the internal surface of the top substrate, and positioned on the cavity central axis. The detectors are filled with an operating gas to 740 Torr and then closed with a shut-off valve. They have been operated in both a gas discharge mode (GD) and in a Townsend avalanche (TA) mode. The resulting signals for avalanche and discharge modes have mV to volt amplitudes with approximately 1 to 3 ns rise times. In both operational modes signals are initiated by ionizing radiation traversing the pixel gas volume and producing primary and secondary ion-pairs that lead to avalanche multiplication. The GD mode uses a Ne + Ar Penning mixture [3] with a fraction of CF_4 and a gas fill pressure of 740 Torr. This mode can be considered Geiger-like in that it yields very large gains of order 10^9, large amplitude volt-level signals which can be easily read out without amplification [4]. The avalanche leads to streamer formation and gas breakdown that collapses the internal electrical field and terminates the discharge. An external quench resistor is used to connect each pixel to its high voltage bus line. This resistance, combined with the pixel capacitance, sets a recovery time of the pixel. Resistances of 500 MΩ and 1 GΩ were used, with results from the latter included here. Pixel capacitance is of order 0.5–1 pF, measured with an LCR meter. The recovery time allows full neutralization of ions and prevents signal regeneration. While the single pixel recovery time is many hundreds of μsec, limiting the maximum single pixel rate, the array of independent pixels potentially allows a higher rate capability. Operation in TA mode is done with the GD mode quench resistors left in place. TA mode produces small, mV level signals that require amplification before they can be discriminated. Unlike in GD mode, many fewer ions and electrons are formed in the avalanche process, the electric field remains established and the pixel can respond to higher rates. The rate capability is ultimately limited by space charge effects. In TA mode the operating gas was pure CF_4 or CF_4 combined with C_2F_6 at 740 Torr. Results from both GD and TA modes are reported in the following.

A μHex detector with its gas port and fill tube is shown in Fig. 1. Insets show the pixels and quench resistors. The pixel inset also shows the readout lines. These lines connect to the anodes through the conductive vias which are masked off in the image. The ribbon cables are used both to convey the high voltage to each row of pixels and for read out of each column of pixels. Preparation of the detector for operation includes baking at moderate temperatures to accelerate outgassing of impurities, extensive pump down and evacuation of the fill tube and cavity volumes, and backfilling with the particular operating gas. The gas is prepared *in situ* by a gas mixing station using mass flow controllers. The gas mixing precision is estimated to be ±5% in the fraction of any gas component. The large fill tube provides a gas reservoir of many tens of cc's in addition to the small gas volume. After backfilling of the desired gas mixture a permanent valve (not shown in Fig. 1) on the fill tube is closed. In this condition, detectors have been operated in both modes months after a fill has occurred. In GD mode readout is done by extracting the signal from termination resistors on each readout line and routing them to discriminators and to a multi-channel scaler or attenuated and sent to a front-end TDC/ADC system [5] that has been repurposed from another application. In TA mode signals are either delivered to standalone amplifiers and discriminated or read out directly (unattenuated) by the same TDC/ADC system.

2. Experimental results

The performance of the μHex was evaluated initially in GD mode. Experiments reported here addressed pixel efficiency and pixel isolation. Subsequently it was determined that TA mode offered higher rate capability, and further testing was done in this mode. For both modes of operation a field of 128 pixels (of which 125 were known to have functioning high voltage connections) was instrumented for readout using 1 GΩ quench resistors on each pixel. In GD mode, the detector was filled with the Ne-based gas and operated over a range from −900 to −1100 V. Experiments and measurements were conducted using a β radiation source and cosmic ray muons. Reported below are results for pixel isolation and the efficiency to detect near-minimum ionizing cosmic ray muons. In TA mode measurements of rates, rate stability and time resolution were conducted and herein reported.

2.1. Pixel isolation

As noted above, μHex pixels are designed to operate as independent, isolated detection units, an intended result of the metalized pixel cavity walls which provide both electrical and optical isolation. The pixel isolation was investigated in GD mode by irradiating the detector with a ^{90}Sr β source, collimated to 1 mm diameter. The source was robotically translated in 250 μm increments over the full XY coordinate detector area, with the collimator aperture transverse to the plane of the detector. Sixteen readout lines of eight pixels per line were read out using a simple discriminator and multi-channel scaler. Fig. 2 shows the hit distributions obtained for a single readout line when the whole pixel array is active. This plot demonstrates that each pixel generates an approximately equal hit rate response when exposed to the collimated βs. Furthermore, when the β flux is off of the pixel associated to the readout line in Fig. 2, but positioned on any of the other pixels, this readout line registers very few hits, which were strays from the source. The background rates for off-pixel collimator positions were much less than 1 Hz, and the background rate when no source is near the detector was negligible. A similar plot in Fig. 3 displays the hit rates of *all* readout lines combined in the scan and shows, qualitatively, the 125 active pixel boundaries. Noticeable are also three hole or zero rate regions of inactive pixels to which the high voltage bus lines were not connected.

2.2. Cosmic ray muon sensitivity

The response of the μHex to cosmic ray muons was measured in GD mode. Sea level cosmic ray muons have an average energy of 1–4 GeV [6] and are near-minimum ionizing. The detector efficiency is likely to be lower in GD mode, which uses a Ne-majority gas, than in TA mode which uses mostly CF_4, as the Ne gas yields over four times fewer primary ion-pairs per unit track length through the pixel gas volume [7]. Detection of cosmic muons was done using an experimental configuration that consisted of the μHex positioned between two paddles of a plastic scintillator hodoscope. The pixel array comprised of 125 working pixels was instrumented for this measurement. An efficiency, ϵ, was determined from: $\left(\frac{N_{coinc}}{N_{scint}}\right)_{exp} = \epsilon \times \left(\frac{N_{coinc}}{N_{scint}}\right)_{MC}$ where N_{scint} is the number of hodoscope hits, N_{coinc} is the number of μHex plus hodoscope coincident hits within a 1 μs time window. The left side of the equation is experimentally measured and the right side is estimated using a GEANT4 [8] Monte Carlo (MC) simulation that models the hodoscope and μHex detector geometry, the cosmic muon $cos^2(\theta)$ angular distribution [6], and the hodoscope spatial non-uniformities. The efficiency is plotted in Fig. 4 as a function of the high voltage. The error bars are determined by the statistical errors and the uncertainty in the geometrical configuration and scintillator efficiencies. A plateau from −1000 to −1060 V indicates an operating region of maximum efficiency. The vertical axis is the total pixel efficiency. A fit to the plateau gives $\epsilon = 0.58 \pm 0.01$ (fit error). This reported efficiency is lower than unity because the MC generates all possible track lengths through the pixel, including near zero-length tracks that clip the corners of the pixel gas volume. The short track lengths of near-minimum ionizing particles in the Ne-based gas, have less than unity Poisson probability to generate a primary ion pair necessary to initiate a signal. The measurement setup, in contrast to the MC, did not allow to constrain the tracks to near the vertical axis or specify a minimal track length through the pixel volume. The shaded region represents an estimated maximum single pixel efficiency based on the MC. It includes the

Fig. 1. Assembled detector with gas fill port, readout and high voltage feed cables. The gas feed tube connects to a shut-off valve, not shown. Left inset: cavities with readout bus lines. Right inset: array of quench resistors. Color online.

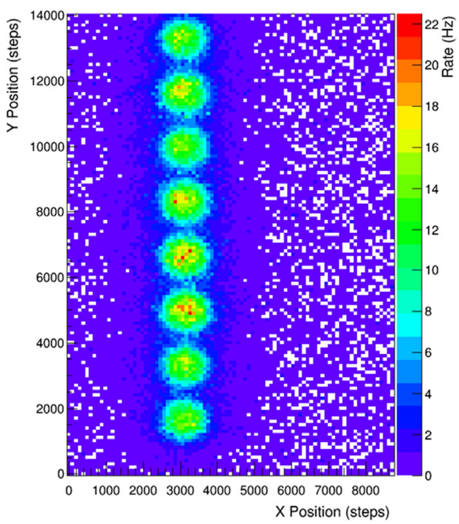

Fig. 2. Hit rate as a function of the XY position of a 1 mm collimated β flux scanning over the detector surface. Data from one representative readout line is shown. One "step" unit on the X or Y axis corresponds to 4 μm steps of the stepper motor. The 9000 step range is 3.6 cm. Color online.

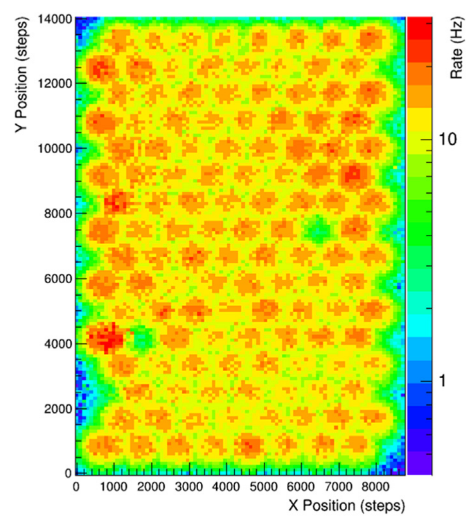

Fig. 3. Hit rate as a function of the XY position of a 1 mm collimated beam scanning over the detector surface. Data from all readout lines are shown. One "step" unit as described in Fig. 2. Color online.

track length distribution, the specific gas primary ion-pair production parameters, the muon sea-level energy spectrum [9] and the angular distribution, and the Poisson probability that at least one primary ion-pair is produced by the track. The width of this region represents the combined systematic uncertainties of these parameters.

2.3. Hit rate and stability

The single pixel hit rates were measured in TA mode. The gas fill was majority CF_4 with C_2F_6 at 740 Torr. With this gas, operating voltages extended from −2800 to −3400 V. A ^{90}Sr β source was positioned over the pixel. Three source positions were used: h_1, h_2 and h_3 at approximately 3 cm, 1.5 cm above, or directly on the pixel, respectively. Data were acquired at position h_1 for a period of 6.8 days, and at positions h_2 for 3.7 h and h_3 for 7.6 days. The hit rates for each position are reported in Fig. 5, where each data point corresponds to the average rate measured in an eight minute time window. As the source is moved closer to the pixel the hit rates increased as expected.

The measured single pixel rate at position h_1 was 1172 ± 7 (RMS) Hz and was stable to 0.6% over the seven day period. Some drift of this rate of order ± 10 Hz over the course of the measurement was attributed to small variations in background hits, and to drift in the readout electronics discrimination threshold as well. These rate fluctuations were not associated with the detector response. The rate at position h_2 was 3632 ± 13 (RMS) Hz and at position h_3 was 16946 ± 157 (RMS) Hz. At this last position there was an initial diminishment of the measured rate of about 3% in the first 40 h. For the remaining period of data taking (about 143 h) the rate was within 0.5% of the average. When these rates are normalized to the total 4.8 mm^2 pixel area (which includes the insensitive cell walls) they correspond to about 24 kHz/cm^2, 74 kHz/cm^2 and 346 kHz/cm^2, respectively. The highest rate produced in

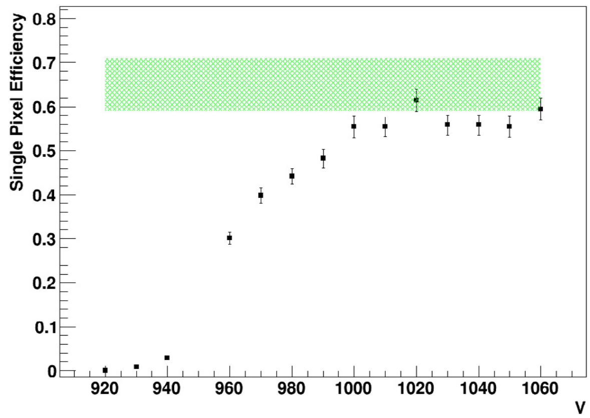

Fig. 4. Single pixel efficiency curve for cosmic ray muons. Error bars are statistical. The shaded region is the estimated maximum single pixel efficiency with systematic uncertainty determined from the MC. The horizontal scale is the applied negative high voltage. Color online.

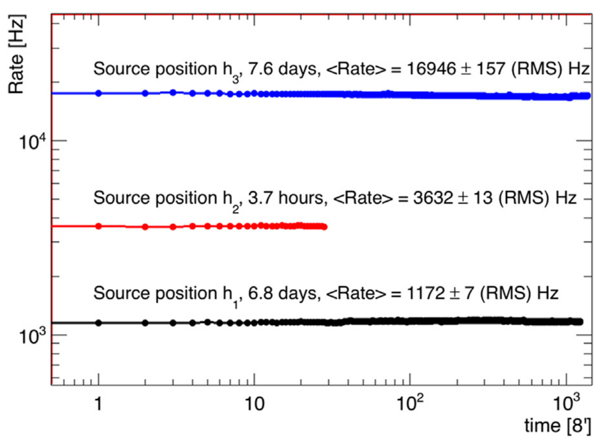

Fig. 5. Single pixel signal rates in TA mode recorded using ^{90}Sr β source at three positions. The horizontal axis has 8 min wide bins. Color online.

this experiment was limited by the source strength and does not imply the maximum rate capability of a μHex pixel.

2.4. Time response

The timing response using the μHex in TA mode was measured using the same scintillator hodoscope and similar geometrical configuration used to detect cosmic ray muons. An array of 128 pixels, of which 125 pixels were operational, was used for this measurement. The gas fill was 100% CF_4 at 740 Torr. The high voltage was set to −3000 V. Data were acquired Time-to-Digital (TDC) system providing 0.78125 ns timing resolution. The hodoscope trigger provided the reference time with an intrinsic 0.9 ns jitter. Fig. 6 shows the arrival time TDC spectrum formed from the μHex recorded hit time subtracted from the hodoscope trigger time. The arbitrary offset is due to various delay constants from cables and electronics. This TDC spectrum represents drift times from hits at any point in the pixel. The narrow width of the spectrum determined from a range-limited Gaussian fit is 2.0±0.15 ns. This width includes also 0.9 ns of trigger jitter. Subtraction in quadrature of this jitter reduces the timing resolution to 1.8 ± 0.15 ns.

3. Summary

Results of the μHex, a pixelated, closed gas detector, have been presented. This device has been evaluated as a high gain Geiger-like gas

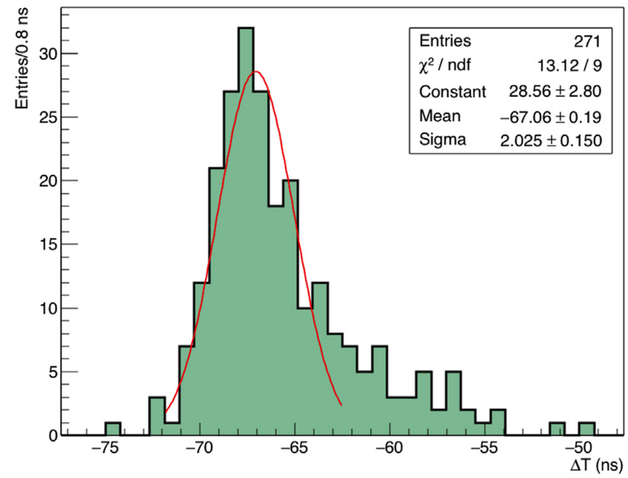

Fig. 6. Arrival time distribution of cosmic ray muon hits in a μHex with respect to the trigger time. The offset is from arbitrary cable and electronic delays. The reported Gaussian parameters are for a fit restricted to the central core of the TDC distribution. Color online.

discharge mode detector using a Ne-based gas and quench resistors at each pixel site, and as a lower gain detector where signals are produced from gas avalanche in a CF_4-majority gas. With a Ne-based gas, the detector was operated in GD mode and had a single pixel efficiency of 58% ± 1%, near the maximum efficiency expected for the gas and pixel geometry used. Improvements in the detector efficiency are the subject of ongoing efforts and are anticipated from larger, deeper pixels and reduced cell wall thickness, and in TA mode using a CF_4-based gas. Overall, the μHex has been shown to function as an array of independent detection units with fast timing. In TA mode the time response for cosmic ray muons relative to a scintillator trigger time is 2 ns, determined by a Gaussian fit to the core of the arrival time spectrum. Furthermore, TA mode hit rate measurements suggest that the detector can operate for extended periods without degradation. A hit rate of 24 kHz/cm^2 was measured to be stable to 0.6% (RMS) over seven days and about 350 kHz/cm^2 at 0.9% RMS variation for nearly eight days of continuous operation.

Acknowledgments

Development of the μHex project was funded by the U.S. National Science Foundation Grant 1506117. The research at Tel Aviv University (TAU) was supported in part by the I-CORE Program of the Planning and Budgeting Committee, (grant no. 1937/12) and the Abramson Center. Support to Integrated Sensors, LLC was provided by the U.S. Department of Energy Office of Nuclear Physics under Award DE-SC0013292 and the National Cancer Institute under Grant 5R44CA183437. Research at TAU and scientific exchange and collaboration between the University of Michigan and TAU was supported by the Israel–United States Binational Science Foundation 2014716. Photographs of the μHex detector were graciously provided by *Natural Portraits and Events Photography* at https://www.naturalportraitsandevents.com.

References

[1] R. Ball, et al., Development of a plasma panel radiation detector, Nucl. Instrum. Methods Phys. Res. A 764 (2014) 122–132.
[2] R. Ball, et al., First results with a microcavity plasma panel detector, Nucl. Instrum. Methods Phys. Res. A 784 (2015) 56–59.
[3] M.J. Druyvesteyn, F.M. Penning, The mechanism of electrical discharges in gases of low pressure, Rev. Mod. Phys. 12 (1940) 87; Rev. Mod. Phys. 13 (1941) 72.
[4] Fabio Sauli, Gaseous Radiation Detectors, Cambridge University Press, Cambridge, UK, ISBN: 978-1-107-04301-5, 2014, p. 206.
[5] Y. Arai, et al., ATLAS Muon drift tube electronics, JINST 3 (2008) P09001, http://iopscience.iop.org/1748-0221/3/09/P09001.

[6] M. Tanabashi, et al., (Particle data group), Phys. Rev. D 98 (2018) 030001.
[7] A. Sharma, “Properties of some gas mixtures used in tracking detectors” International Committee for Future Accelerators ICFA Bulletin 16 1998 http://www.slac.stanford.edu/pubs/icfa/summer98/paper3/paper3.pdf.
[8] S. Agostinelli, et al., Geant4 simulation toolkit, Nucl. Instrum. Methods Phys. Res. A 506 (3) (2003) 250–303.
[9] K. Borozdin, T. Asaki, R. Chartrand, M. Galassi, A. Greene, Cosmic-Ray Muon Tomography and its Application to the Detection of High-Z Materials, 2018. https://www.researchgate.net/publication/242511120.