Development and First Tests of GEM-Like Detectors With Resistive Electrodes

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***Abstract*—We have developed and tested several prototypes of GEM-like detectors with electrodes coated with resistive layers or completely made of resistive materials. These detectors can operate stably at gains close to 10^5. The resistive layers limit the energy of discharges appearing at higher gains thus making the detectors very robust. We demonstrated that the cathodes of some of these detectors could be coated by CsI or SbCs layers to enhance the detection efficiency for the UV and visible photons. We also discovered that such detectors can operate stably in the cascade mode and high overall gains ($\sim 10^6$) are reachable. Applications in several areas, for example in RICH or in noble liquid TPCs are therefore possible. The first results from the detection of UV photons at room and cryogenic temperatures will be given.**

***Index Terms*—CsI photocathode, GEM, noble liquids TPC.**

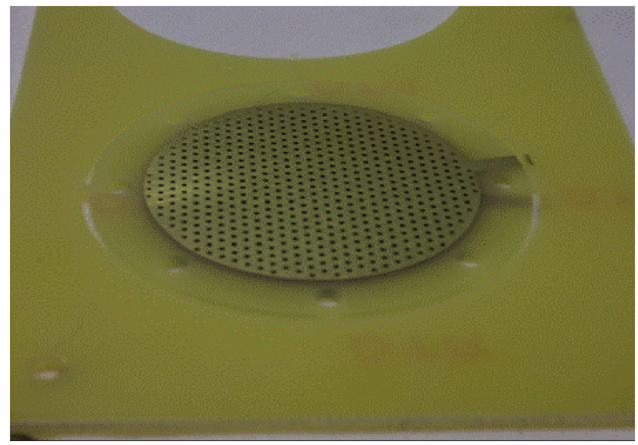

Fig. 1. A photograph of a TGEM.

I. Introduction

RECENTLY developed hole-type gaseous detectors [1]–[3] have opened new directions in the detection of photons and charged particles since they can operate at relatively high gains in poorly quenched gas mixtures (see, for example, [4]–[7]). Nowadays, the most popular hole-type detector is the so-called Gas Electron Multiplier (GEM) [3]. Cascaded GEM structures have been implemented in the layout of several large scale high-energy physics experiments [8]. However, the GEM is a rather fragile detector since it requires dust-free conditions during the assembly phase and could be easily damaged by sparks, almost unavoidable at high gains of operation. Several groups tried to lower the sparking rate and the subsequent damaging effect by using either segmented GEMs [9], or many GEMs (up to 4–5) in cascaded mode [10] or by identifying the optimal combination of the design parameters (the width of the gaps between the cascaded GEMs, the voltage values at a given counting rate, and so on), which ensure the minimum rate of sparks at the given overall gain by respecting the "safe operational setting" [11].

This paper reports our contribution to these efforts.

Our studies show that the maximum achievable gain increases with the thickness of hole-type detectors [12]. On this basis we firstly developed and studied the performance of a thick GEM (TGEM) [7], [13], [14] made of printed circuit board, with a metallic coating on both sides bearing drilled holes (Fig. 1). This simple device allows to achieve a maximum gain ten times higher than that of a conventional GEM [14]. Subsequently we modified this detector by drilling out a Cu layer around each hole; this allowed to further increase the maximum achievable gain by a factor of about five. A systematic study of this device was performed by Breskin's group: they confirmed the robustness of the detector, which can operate at gains of $\sim 10^5$. Instead of drilling out the Cu around the edges of the holes, they manufactured the protective dielectric rims by means of a lithographic technology [15].

Recently we have developed and tested a thick GEM whose electrodes were coated by a layer of graphite paint [16]. We named this detector a Resistive Electrode Thick GEM or RETGEM. The RETGEM could operate at gains of $\sim 10^5$; at higher gains, a streamer mode occurs enabling operation as a photon counter. Conversely to sparks in conventional GEMs, streamers produced in RETGEM are mild (see Fig. 2) and do not damage neither the detector nor the front-end electronics.

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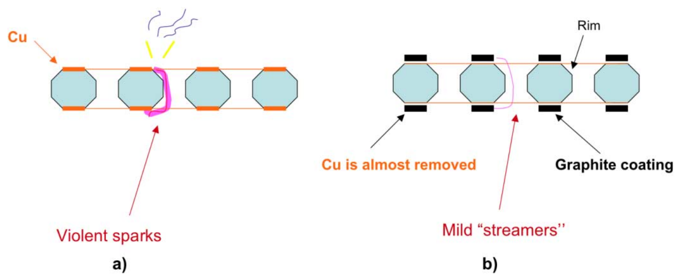

Fig. 2. A schematic drawing showing the difference between the behavior of GEMs and RETGEMs. In the case of the GEM detector (a) all electrical energy released by the spark is stored in the detector's capacity; in the case of the resistive coating (RETGEM) the energy released by the discharge is limited by the electrode's resistivity via the charging up effect. For this reason the discharges (streamers) are very mild (b).

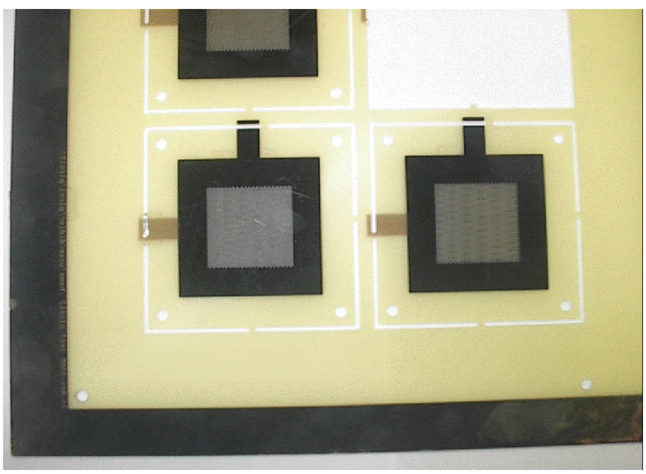

Fig. 3. A photo of the RETGEM (5×5 cm^2) with electrodes coated by CuO resistive layers.

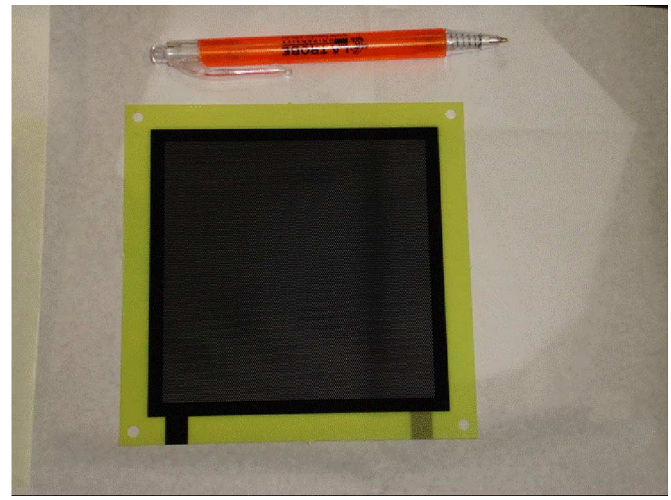

Fig. 4. A photo of the larger (10×10 cm^2) prototype of the RETGEM with CuO electrodes.

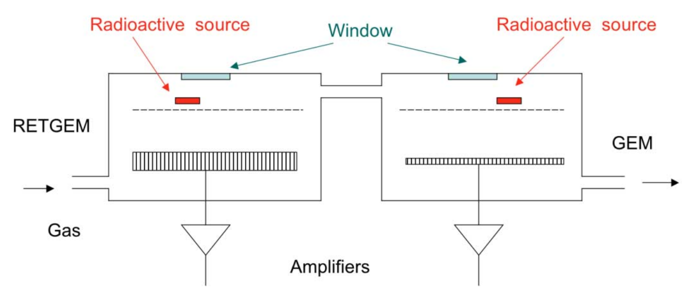

Fig. 5. A schematic drawing of the experimental set up for comparative studies of the RETGEMs and the GEMs.

Not only the graphite coating but also many other resistive layers could be used to achieve the same effect. The most important issue in the production of such types of detector is to use a technology which ensures high quality and reproducibility of resistive coatings during the mass production.

The aim of our work was to build and test simple prototypes of RETGEMs made by a combination of the CNC machining and lithographic technology. Results from the first applications of these devices to UV photon detection at room and cryogenic temperatures will be presented hereafter.

II. RETGEMs With CuO or CrO Coated Electrodes

As in our previous work [16], the RETGEMs employed in these studies were manufactured by coating TGEMs electrodes with resistive layers. The last ones were produced from G-10 sheets (3×3, 5×5 or 10×10 cm^2 active area) using the industrial PCB processing of precise drilling and etching. The TGEM used were 0.4–1.5 mm thick with holes of 0.3–1 mm in diameter and with a pitch of 0.7–2.5 mm, respectively. Their electrodes were made of Cu or Cr and in all detectors the electrodes were etched around the hole edges in order to remove sharp edges and create dielectric rims of 0.1–0.15 mm in width. For the sake of simplicity, the resistive coating was produced through the oxidation of the metallic electrodes. The photographs of the first prototypes of these detectors are presented in Figs. 3 and 4.

Note that these detectors were very different from our first prototypes, described in [16], in which the Cu electrodes were etched until they became very thin and nonuniform in structure, then they were coated by thick graphite layers and the edges of the hole were then additionally drilled out to remove the sharp edges. It was not clear in advance if these new designs (with CuO or CrO layers) would have provided any spark protection.

The experimental set up for the study of the performance of these detectors is shown in Fig. 5. It contains two gas chambers connected together by a pipe line and flushed by the same gas at a pressure of 1 atm. In one of the chambers, a RETGEM was installed and in the other one, a GEM, which we used for comparative studies. Most of the GEMs used in these studies had sizes of 10×10 cm^2 and were manufactured at CERN. However in some studies, GEMs manufactured in the USA [17] were also used. As ionization sources, ^{55}Fe or ^{241}Am radioactive sources placed inside the chambers were used. Signals from the detectors were recorded by the charge sensitive amplifiers Ortec142A and CANBERRA 2006. The amplifiers were calibrated by a standard procedure of a given charge injection to their input circuits (in other words, the output signals from the amplifiers were measured for the known charge injected to their inputs). The cross check of this calibration was done with the ^{241}Am alpha source which allowed one to observe the signals from the amplifiers even at gain of 1 and thus was very convenient for the calibration in the gain interval of 1–100 (see Section IV).

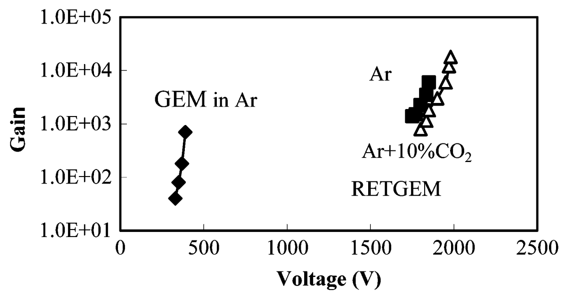

Fig. 6. Gains vs. voltage for the GEM operating in Ar and for the RETGEM (1 mm thick) flushed with Ar and Ar $+$ 10%CO_2.

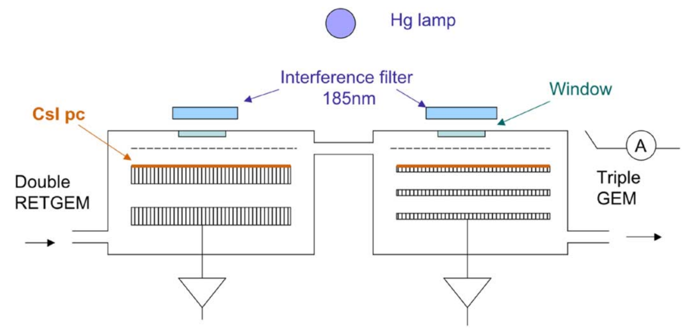

Fig. 7. A schematic drawing of the experimental set up used for comparative studies of photosensitive double RETGEMs and triple GEMs.

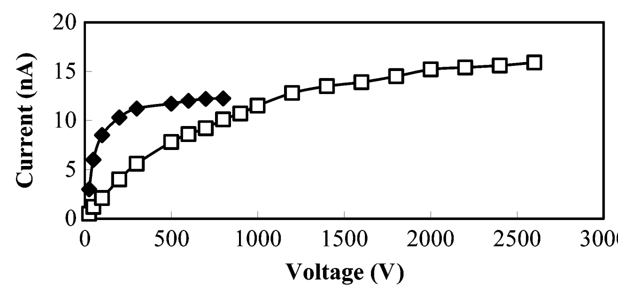

Fig. 8. Current measured by a photodiode R1259 (diamonds) and from the CsI cathode of the upper GEM (squares) in CH_4. Note that at high voltages both currents reached plateau: $I_{PD} = 12.2$ nA and $I_{GEM} = 15.9$ nA.

Some results from the measurement of the gain as a function of the voltage applied across the detector's electrodes are presented in Fig. 6. The measurements were stopped at values of voltages producing first signs of gain instability. One can see from this data that the RETGEM operates stably in pure Ar at gains of 10 times higher than those of the GEM. At gains close to 10^5, discharges may appear in the RETGEM. Because the oxide layers were much thinner than the graphite coating we used in the earlier studies [16], the discharges in the present version of the RETGEM were not mild streamers, but rather sparks. However, the energy released in these sparks was lower then in the case of the TGEMs and as a result the detector was more robust than the TGEM or GEM.

Because RETGEMs operate at gains much higher than GEMs, it was appealing to use them either for single electron detection or as photodetectors. First results obtained in this application are presented in the next paragraph.

III. Tests of RETGEM-Based Photodetectors

Several groups (see for example [6], [18], [19] demonstrated that cascaded GEMs (3–4 GEMs operating in tandem) combined with semitransparent or reflective CsI photocathodes could be used for the detection of UV and even visible photons [19]. This detector's configuration offers new possibilities in some applications, for example in the detection of the Cherenkov light. Indeed GEMs with reflective photocathodes can operate and remain high sensitive to light at zero or even at reversed drift electric field being in such a way a "hadron blind" (see [20] for more details). Moreover, in some cases GEMs can be placed and be operated in the same gas used as a Cherenkov radiator so that no separation windows are needed between them.

Therefore it seems interesting to evaluate if the RETGEM can offer a comparable or even better performance.

Because the RETGEM has a dielectric coating it is not clear in advance if it could be coated with a CsI film or any other photosensitive layers and if these layers remain stable and have a high enough quantum efficiency. It was not evident as well whether these detectors can operate stably in cascaded mode. To answer these questions and investigate other potential problems we built prototypes of cascaded RETGEMs combined with CsI or SbCs photocathodes and performed some preliminary tests.

A. Tests Oriented to RICH Applications

1) RETGEMs With CsI Photocathodes: For these tests, we slightly modified the experimental set up shown in Fig. 5. Inside the first chamber two RETGEMs operating in cascade mode were installed (we named them "double RETGEMs" and inside the other one—three cascaded GEMs ("triple" GEMs) with Cu electrodes manufactured by Tech-Etch Inc. [17], see Fig. 7. The cathode of the upper RETGEM and the Cu cathode of the upper GEM were coated with a CsI layer 400 nm thick (by a vacuum deposition technique). From our earlier experience we know that the Cu substrate may cause a rather fast degradation of the CsI quantum efficiency (QE), this is why it was very important not only to measure the initial value of the QE immediately after the CsI evaporation but also to monitor it in time. This was done with the help of a Hg lamp. The UV light from the Hg lamp entered the detectors via the CaF_2 windows covered with narrow band filters having a peak transmission at 185 nm. By applying a negative (reversed) voltage between the upper GEM electrode with the CsI photocathode and the drift mesh, the photocurrent was measured in various gases as a function of this voltage. In CH_4 and in some mixtures of noble gases with quenchers, this photocurrent reaches a plateau at high voltages with a value of I_{GEM} (see Fig. 8) which could be interpreted as "full" collection of the photoelectron from the photocathode.

To evaluate from these data the CsI-GEM's QE we used photodiodes R1259 and R1187 calibrated by Hamamatsu. The photocurrent from these photodiodes exhibited a very clear plateau (with a value at the plateau I_{PD}) and by comparison the values of these photocurrents and taking into account the solid angles at which the UV light reached the detectors, one can calculate the QE of the CsI-GEM being 13.3% in CH_4. This rather high QE was achieved due to the implementation of a special post evaporation heat treatment of the photocathode (see [21] for more details) which was not used in earlier developments performed for example by the RD26 collaboration. In addition, after the evaporation, the CsI photocathode was not exposed to any strong UV or visible lights and this reduces photochemical interaction of the CsI with the Cu substrate (which may cause the CsI QE degradation with time). Of course, for the evaluation of the GEM's quantum efficiency operating in the single electron counting mode (Q_{pract}) one has to take into consideration the photoelectron collection factor ε (see [22] for details) which could be obtained for example, from the measurements of current I_A from the anode of the bottom GEM ($\varepsilon = I_{GEM}/I_A$). However, in our measurements we observed that the I_A steadily increased with the applied voltages (no clear plateau was observed) and thus these simple measurements did not provide any reliable data for the calculation of the Q_{pract}. Obviously, the measurements should be performed in counting mode as was done in [22] and this will be our future task. However, coming from the results presented in [22], one can expect that $\varepsilon \sim 1$ at overall gains of triple GEMs $\sim 10^4$.

We also tried to perform the same current measurements in the case of the RETGEM. Unfortunately, a rather strong charging up effect was observed, even at small values of the photocurrent, so we did not consider these measurements to be reliable for further interpretation. To compare the practical quantum efficiency of the CsI-GEM and the CsI-RETGEM we performed measurements in a counting mode. For this the UV light from the Hg lamp was very strongly attenuated (to achieve a single electron counting mode) and we measured under the identical conditions the counting rates from the GEM (n_{GEM}) and the RETGEM (n_{RETGEM}). For the same overall gains of 10^4 and the same electronics threshold the ratio of the counting was $n_{RETGEM}/n_{GEM} = 1.73$. If one assumes that $\varepsilon \sim 1$ even in the case of RETGEM, than the estimated QE for CsI-RETGEM in CH_4 will be $Q_{\mathrm{pract}} \sim 23\%$. Note that in CH_4 the ratio n_{RETGEM}/n_{GEM} remained practically the same in the overall gain interval of $10^4 - 5 \times 10^4$. However at gains $>3.5 \times 10^4$ the triple CsI-GEMs in CH_4 started operating unstably due to the appearance of sporadic discharges.

Of course in the next experiments we will measure the value of ε and this will allow to estimate Q_{pract} more accurately. However, in this first stage of the work it was important just to have a rough estimate of the Q_{pract} in order to be sure it has a reasonably high value even in the case of the CuO substrate and to monitor the photocathode's stability in time. The last task was achieved by regular measurements of the counting rates from the GEM and the RETGEM under identical conditions over a period of four months. No big changes in the counting rates were observed (the variations were on the level of 10% only) either for the GEM or the RETGEM indicating that the CsI photocathodes remained stable for both detectors.

We also performed comparative measurements of maximum gains achievable with double RETGEMs and triple GEMs both coated with the CsI layers. Some results are presented in Figs. 9 and 10. The measurements were stopped at voltages when first signs of discharges appeared. One can see from this data that in the case of pure Ne and Ar, double RETGEMs offer much higher gains than triple GEMs. This feature makes the RETGEM very attractive for RICH applications. One should note that the gas gain in Ne due to the Penning effect could be very sensitive to the tiny concentration of impurities. To minimize the effect of impurities we used a rather clean Ne (99.9995% pure) and during the measurements the test chambers were flushed at about 6 l/min (the total volume of two test chambers was ~4 l)

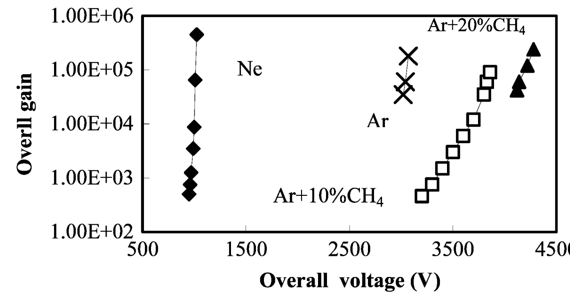

Fig. 9. Gain as a function of applied voltage (to the resistive chain divider) of double RETGEM as measured in various gases.

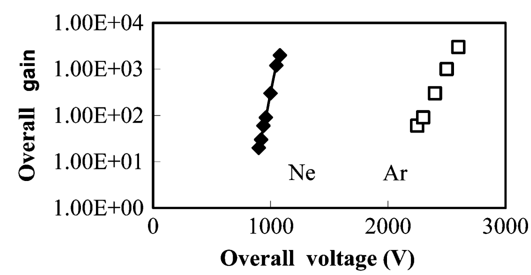

Fig. 10. Gain vs. voltage (applied to the resistive chain divider) for triple GEMs measured in Ne and Ar.

2) RETGEMs with SbCs Photocathodes: The next sets of experiments were performed in order to investigate if another photocathodes (for example, one that is sensitive to visible light) could be deposited on the top of the CuO substrate and if it could remain stable afterwards.

The manufacturing of high quality photocathode sensitive to visible light is a quite complicated procedure [23], [24]. However, some low efficiency photocathodes could be produced in a rather simple way by coating the selected substrate by Cs release from the "Cs generator" [25] in a vacuum of 10^{-6} Torr. In this work, we used this simple technology. One of the surfaces of the RETGEM (size of 3×3 cm^2, 1.5 mm thick) was coated by a Sb layer 0.2 μm thick through a vacuum deposition technique. The RETGEM was then extracted from the evaporation set up and placed inside a quartz tube (the inner diameter of which was 70 mm) and which had several electrical feedthroughs in its metallic flanges, see Fig. 11. The tube with the RETGEM was heated to $\sim 100^\circ$ C and pumped to a vacuum of 10^{-6} Torr for several days. It was then cooled down to room temperature and the Cs generator was activated; Cs vapor released from the generator reacted with the Sb surface and finally formed SbCs. The main problem associated with this primitive technique is the excess of Cs remaining on the inner walls of the tube and on the surfaces of feedthroughs. Sometime there were cases of current instabilities during the measurements. However, we succeeded to move the Cs depositions out from the chamber into the pumping system by local heating of the contaminated parts of the tube by a small flame. Finally the detector was then again heated to remove the remaining excess Cs. After such cleansing

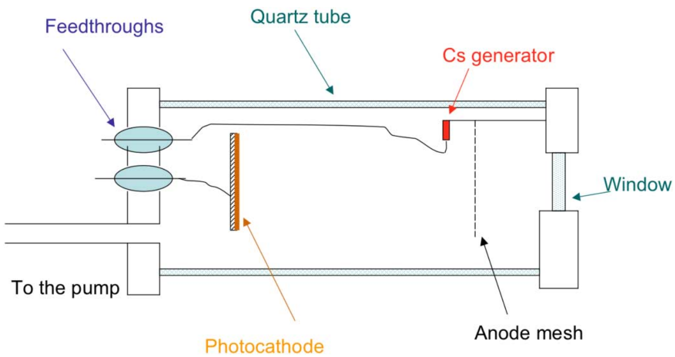

Fig. 11. A schematic drawing of the set up used for manufacturing SbCs photocathode on the top of the RETGEM.

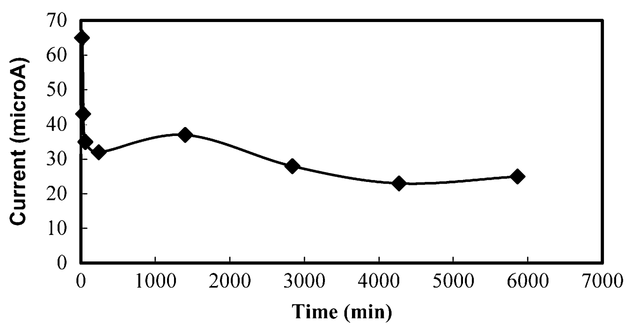

Fig. 12. Photocurrent vs. time as measured in vacuum between the cathode and the anode mesh soon after manufacturing the SbCs photocathode.

procedures we were able to perform measurements of the photocurrent produced by a lamp and monitor the stability of the photocathode with time. Some our first results are presented in Fig. 12. One can see that immediately after the photocathode's manufacturing, the photocurrent dropped very steadily, but then "stabilized" and began to degrade quite slowly so that we had enough time to measure the photocathode's QE. In this case, the tube was attached to the monochromator (combined with a Hg or H_2 lamp) and the photocurrent $I_d(\lambda)$ produced in the detector by the light from the photon spectrometer was measured as a function of the wavelength. After these measurements were completed, the quartz tube was replaced by a Hamamatsu calibrated photodiode R414 and for each wavelength we measured the photocurrent from the photodiode $I_{PD}(\lambda)$ produced by the light beam exiting the monohromator. From the known absolute QE of the photodiode R414 and the ratio $I_d(\lambda)/I_{PD}(\lambda)$ the QE of the SbCs-RETGEM was calculated. Some of our fist preliminary results are shown in Fig. 13. One can see that the quantum efficiency achieved by such a manufacturing technique was 2–3 times lower than that achieved with high quality photocathodes. However, we consider these preliminary results as rather encouraging, because we believe that in the future developments we will be able to protect the SbCs photocathodes deposited on the top side of the RETGEMs by a thin ($\sim$20 nm) CsI layer.

This technique was first described in [25] and subsequently it was further developed by Breskin's group (see for example [26] and reference therein). For the time being however, we coated the SbCs-RETGEM by a very thick ($\sim$100 nm) CsI layer using a conventional evaporation set up and the RETGEM was then

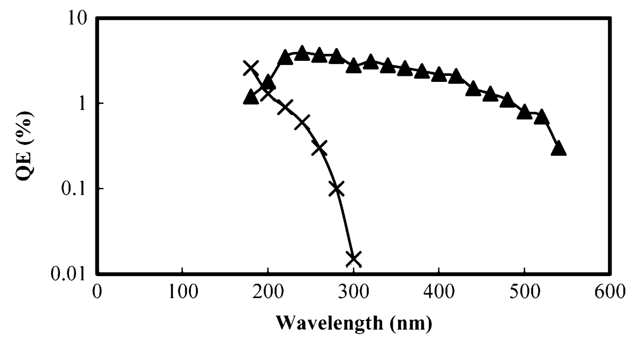

Fig. 13. Results of the QE measurements: triangles—SbCs photocathode, crosses—SbCs photocathode covered by a CsI protective layer.

extracted in air and placed inside the quartz tube which was then immediately evacuated.

The results of the measurements of the QE of such photocathode exposed for a few minutes to air are present in Fig. 13. This photocathode did not show any signs of degradation during one week monitoring of its QE under vacuum. Certainly, more tests are needed to demonstrate that RETGEMs coated with SbCs or SbCs/CsI photocathodes could stably operate in gas conditions.

B. Tests Oriented on Applications for Noble Liquid TPCs

In the work [27] it was shown that triple bare GEMs can operate at gains of 5×10^3 in a double-phase Ar detector. The focus of our earlier works was on the study of operation of the GEM and other hole-type detectors combined with CsI photocathodes at cryogenic temperatures. For example, in [28] we demonstrated that TGEMs coated with CsI photocathodes can operate at cryogenic temperatures and detect the scintillation light from noble liquids (see also [29]).

It will be interesting to check if RETGEMs, in spite of their resistive electrodes, can also operate stably at cryogenic temperatures especially in the case when they are coated with a CsI layer. To verify this, we have performed several sets of measurements with single and double RETGEMs cooled to cryogenic temperatures.

Our experimental set up was the same as in [29] and it is shown schematically in Fig. 14. It consists of the cryostat with a test chamber placed inside it. The temperature in the cryostat was controlled by a computer and can be changed from room to $\sim$77 K. Depending on the measurements, either a single or a double RETGEMs (1 mm or 1.5 mm thick) with the top electrode coated with a CsI layer was installed inside the chamber (see Fig. 14) as well as a radioactive source ^{55}Fe for gas gain measurements. In some experiments an additional scintillation chamber (see [29] for more details) was attached to the test chamber and flushed by Ar at a pressure of 1 atm; it contained an ^{241}Am alpha source inside. Figs. 15 and 16 show gain vs. voltage curves measured at room temperature and 100 K for RETGEMs 1 and 1.5 mm thick, respectively. One can see that gains of 10^4 could be achieved at 100 K with double RETGEMs. Because of our test chamber was flushed with Ar at a pressure of $\sim$1 atm we could, if necessary, liquefy Ar inside the chamber and investigate the operation of the RETGEM in the case when

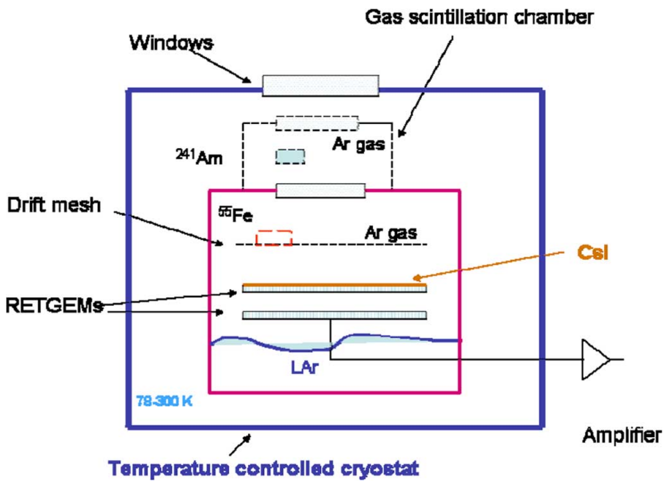

Fig. 14. A schematic drawing of the set up used for measurements with RETGEMs at cryogenic temperatures.

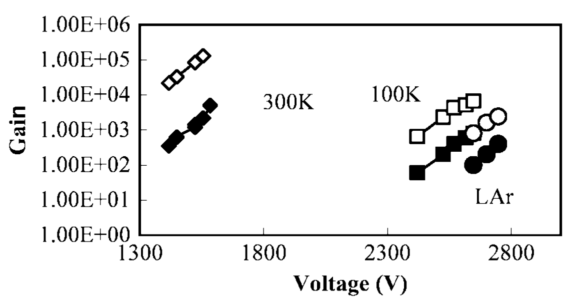

Fig. 15. Gain vs. voltage for a single (filled symbols) and for a double (open symbols) RETGEM (1 mm thick) as measured in Ar at room temperature and pressure p = 1 atm and at 100 K, p = 1 atm (rhombus) and finally in the case when the RETGEM was 1–2 cm above LAr level at T ∼89 K, p = 1.1 atm (circles).

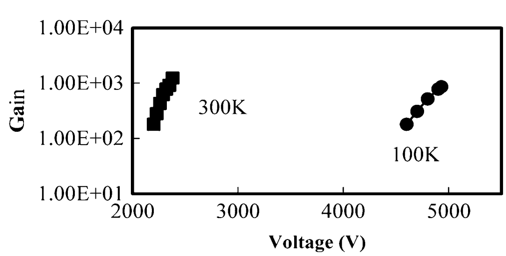

Fig. 16. Gain vs. voltage for a RETGEM (1.5 mm thick) as measured in Ar at 1 atm at room temperature (diamonds) and 100 K (squares).

the LAr level was just 1–2 cm below the anode of the RETGEM (see Fig. 14). The level of the liquid inside the chamber was measured by a capacitor meter and one can also independently monitor it via the window. Results of gain measurements in this condition are shown in Fig. 15. One can see that compared to the case where the RETGEM operated in Ar at 100 K, the operating voltage of the RETGEM placed 1–2 cm above the LAr level was higher. This could either be due to the higher gas density around the RETGEM or due to a thin layer of LAr formed on the surface of the RETGEM.

Because of the intensity of the alpha source used was rather low, we could not perform the QE measurements in the current mode as it was done in the previous experiments. The Q_{pract} of the CsI photocathode at various temperatures was estimated from the amplitude of the signal B (in electrons) from the CsI-RETGEM detecting the scintillation light produced by alpha particles:

$$B = AN_{\mathrm{ph}}\Omega Q_{\mathrm{pract}}, \tag{1}$$

where A is a gas gain, N_{ph} is the number of UV photons emitted by the alpha source, and Ω is a solid angle at which the scintillation light reaches the CsI cathode. The value of B (in electrons) was calculated from the measured amplitude of the signal and the known response of the amplifier on the given injected charge to its input circuit. The cross check of this calibration was done from the measured ratio of the scintillation signal to the ionization signal produced by the ^{55}Fe source (see [7] for more details). The number of photons produced by the alpha particles was calculated from the following expression:

$$N_{\mathrm{ph}} = E/W, \tag{2}$$

(E is the energy of alpha particles and W is the energy required to produce a UV photon. The value of W ($W \approx 50$ eV) was taken from the experimental work [30]. One should note that in the pressure interval where the W value is well known this method of the detector's QE calibration is rather precise and was successfully used by several author for the calibration of avalanche photodiodes (see for example [31] for more details). Assuming that both N_{ph} and W are independent on the temperature, the calculated Q_{pract} was then 28% and 17% at room temperature and 100 K, respectively. These very preliminary results demonstrate that RETGEMs could be an attractive alternative to PMTs or any other type of photodetectors for noble liquid TPCs.

IV. First Results Obtained With RETGEMs Made of a Single Layer of Resistive Materials

RETGEMs described in this work and in the previous one [16], [32] are simple prototypes and are far from being ideal. For example, one of the problems of the RETGEMs with the CuO or CrO layers is that at high gains they transit to weak sparks rather than to mild streamers.

Both these RETGEM designs had double- layer electrodes structures: a thin Cu layer and a resistive layer on its upper layer.

The subsequent step of our work was to build and test first prototypes of RETGEMs with electrodes made of single-layer resistive materials [33]. They were manufactured from standard printed circuit boards (PCBs) having a thickness of 1, 1.6 or 2.4 mm. On the both surfaces of the PCB sheets resistive Kapton 100XC10E5 foils 50 μm thick were glued (the glue used was FR4). The surface resistivity of this material, depending on a particular sample, may vary from 500 to 800 k$\Omega/\Box$. The holes were drilled by a CNC machine as was done earlier in the case of TGEM; they were 0.8 mm in diameter, the pitch was 1.2 mm and the active area of the detector was 30 × 30 mm^2. A Cu frame was manufactured by a photolithographic technique in the surrounding area of the detector in order to provide good electrical contacts with the HV and signal cables-see Fig. 17.

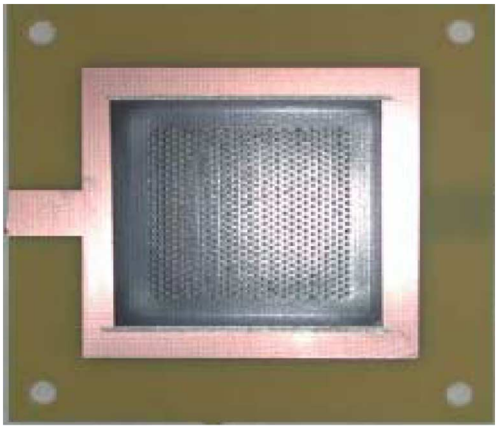

Fig. 17. A photo of a RETGEM with electrodes made of resistive Kapton.

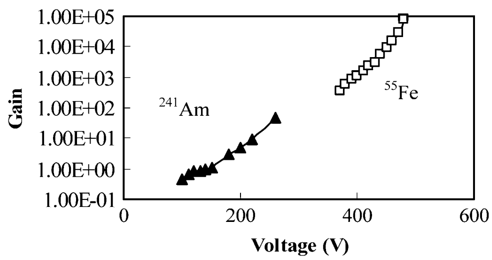

Fig. 18. Gains vs. voltage measured with the first prototype of the RETGEM 1 mm thick using ^{241}Am and a ^{55}Fe radioactive sources.

Fig. 18 shows gain vs. voltage measured in the case of the kapton RETGEM 1 mm thick operated in pure Ne. Measurements were performed using ^{241}Am at low gains and ^{55}Fe at high gains. One can see that in the case of the ^{55}Fe source gains close to 10 ^{5} were achieved. At higher gains the detector transited to mild streamers which did not harm either the detector or the preamplifier. One can also notice that the extrapolation of the Am gain curve do not exactly match the data for ^{55} Fe. We explain this by the RETGEM's charging up effect.

In Ar, which requires much higher voltages, this detector at a gain of $\sim 10^4$ transited to a continuous discharge and the visual observation showed that the discharge was caused by the Kapton microwires sticking out from one of the imperfect holes. However, this continuous discharge was not harmful as well.

Figs. 19 and 20 show the results of gain measurements performed with the 2.4 mm thick RETGEM flushed with Ne, Ar or Ar + 20%CO_2. One can see that a gain close to 10 ^{5} was achieved in Ne and $\sim 10^4$ in Ar and in Ar + 20%CO_2.

At higher gains, streamer type of discharges appeared, which may transit to a continuous discharge with a further increase of the voltage. None of these discharges were destructive.

An interesting effect was observed during these studies: the discharges created in the holes of the RETGEM may propagate along the Kapton surface to the Cu frame. Similar surface streamers were observed by us earlier in the case of microstrip gaseous detectors [34], [35]. Studies show that surface streamers can easily propagate along dielectric surfaces on large distances even in rather weak electric fields [34], [36]. We are now developing another design of the RETGEMS in which the surface steamers will be strongly suppressed.

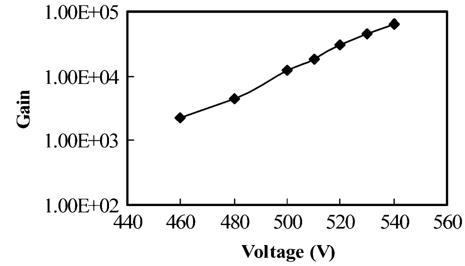

Fig. 19. Gain vs. voltage as measured in Ne with the RETGEM 2.4 mm thick. A radioactive source of ^{55}Fe was used.

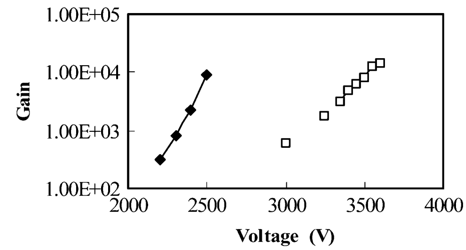

Fig. 20. Gains vs. voltage as measured in Ar (diamonds) and Ar + 20%CO_2 (squares) with the RETGEM 2.4 mm thick. As a radioactive source ^{55}Fe was used.

It was also observed in this work that in the case of the double RETGEMs operating in pure Ar and Ne the discharge in the hole of the bottom RETGEM may trigger discharges between the RETGEMs. Similar effects were observed earlier in the case of double GEMs and this phenomena is well understood today (see for example [11], [37] and references therein). This type of discharge could be avoided by the optimization of the voltages applied to the top and bottom RETGEMs as well as decreasing the voltage between the RETGEMs (or increasing the distance between them) [11].

V. Discussion and Conclusion

The obtained preliminary results demonstrate the potentials of the new detector. In spite of the fact that the RETGEM with "metal-dielectric" electrodes at high gains transits to sparks rather than to a streamer, it is more robust than the GEM or even the TGEM. The other important discovery was that the RETGEM could be combined with photocathodes and can operate in cascade mode.

First tests of RETGEM with Kapton electrodes show that at high gains it transits to mild discharges, which do not damage either the detector or the front-end electronics. Note that achieved gains 10 ^{5} are sufficient for most applications. The RETGEM is very robust, can be assembled in dusty conditions, does not require any special clearness of it surfaces or the gas chamber and the gas system and can operate in poorly quenched gases.

Therefore, we believe that the suggested detectors after some improvements will open new directions for applications which do not require extremely high counting rates or very good position resolutions, for example in RICH, cryogenic TPCs, calorimetry or UV visualization in daylight conditions [16].

Certainly, other resistive coatings could be used as well and the work for their search and study will be the subject of our future projects

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REFERENCES

[1] A. Del Guerra *et al.*, "High resistance lead glass tubing for RICH counters and electromagnetic calorimeters," *Nucl. Instrum. Meth.*, vol. A257, pp. 609–613, 1987.
[2] H. Sakurai *et al.*, "A new proportional counter using a capillary plate," *Nucl. Instrum. Meth.*, vol. A374, pp. 341–344, 1996.
[3] F. Sauli, "GEM: A new concept for electron multiplication in gas detectors," *Nucl. Instrum. Meth.*, vol. A386, pp. 531–534, 1997.
[4] A. Buzulutskov *et al.*, "The GEM photomultiplier operating with noble gas mixtures," *Nucl. Instrum. Meth.*, vol. A443, pp. 164–180, 2000.
[5] V. Peskov *et al.*, "First attempts to combine capillary tubes with photocathodes," *Nucl. Instrum. Meth.*, vol. A433, pp. 492–501, 1999.
[6] T. Francke *et al.*, "Novel position-sensitive gaseous detectors with solid photocathodes," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 3, pt. 2, pp. 977–983, Jun. 2002.
[7] L. Periale *et al.*, "Detection of the primary scintillation light from dense Ar, Kr and Xe with novel photosensitive gaseous detectors," *Nucl. Instrum. Meth.*, vol. A478, pp. 377–383, 2002.
[8] F. Sauli, "Imaging with Gas Electron Multiplier," presented at the Int. Conf. Imaging-2006, Stockholm, Sweden, 2006, submitted to Nucl. Instrum. Meth., unpublished.
[9] C. Altunbas *et al.*, "Construction, test and comissioning of triple-GEM tracking detector for Compass," *Nucl. Instrum. Meth.*, vol. A490, pp. 177–203, 2002.
[10] S. Bachmann *et al.*, "Performance of GEM detectors in high intensity particle beams," *Nucl. Instrum. Meth.*, vol. A470, pp. 548–561, 2001.
[11] M. Wallmarkt *et al.*, "Operating range of a gas electron multiplier for portal imaging," *Nucl. Instrum. Meth.*, vol. A471, pp. 151–155, 2001.
[12] V. Peskov *et al.*, "The study and optimization of new micropattern gaseous detectors for high -rate applications," *IEEE Nucl. Sci.*, vol. 48, no. 4, pt. 1, pp. 1070–1074, Aug. 2001.
[13] L. Periale *et al.*, "Evaluation of various planar gaseous detectors with CsI photocathodes for the detection of primary scintillation light from noble gases," *Nucl. Instrum. Meth.*, vol. A497, pp. 242–248, 2003.
[14] J. Ostling *et al.*, "Study of hole-type gas multiplication structures for portal imaging and other high count rate applications," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 4, pp. 809–819, Aug. 2003.
[15] C. Shalem *et al.*, "Advances in Thick GEM-like gaseous electron multiplier-Part I: Atmospheric pressure operation," *Nucl. Instrum. Meth.*, vol. A558, pp. 475–489, 2006.
[16] I. Rodionov *et al.*, "Advanced gaseous photodetectors for hyperspectroscopy and other applications," in *IEEE Nucl. Sci. Conf. Rec.*, Oct. 2005, vol. 5, pp. 3045–3049.
[17] Tech-Etch. Inc. Plymouth, MA.
[18] F. Sauli, "Novel Cherenkov photon detectors," *Nucl. Instrum. Meth.*, vol. A533, pp. 18–24, 2005.
[19] A. Breskin *et al.*, "Recent advances in gaseous imaging photomultipliers," *Nucl. Instrum. Meth.*, vol. A513, pp. 250–255, 2003.
[20] Z. Fraenkel *et al.*, "A hadron blind detector for the PHENIX experiment at RHIC," *Nucl. Instrum. Meth.*, vol. A546, pp. 466–480, 2005.
[21] H. Hoedlmoser *et al.*, "Production technique and quality evaluation of CsI photocathodes for the ALICE/HMPID detector," *Nucl. Instrum. Meth.*, vol. A566, pp. 338–350, 2006.
[22] D. Mormann *et al.*, "Operation principles and properties of the multi-GEM gaseous photomultiplier with reflective photocathode," *Nucl. Instrum. Meth.*, vol. A530, pp. 258–274, 2004.
[23] S. Giunji *et al.*, "Micro capillary glass plates as a gaseous detector of photons and particles," *Nucl. Instrum. Meth.*, vol. A477, pp. 8–12, 2002.
[24] M. Balcerzyk *et al.*, "Method of preparation and results of sealed gas photomultipliers for visible light," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 4, pp. 847–854, Aug. 2003.
[25] A. Borovik-Romanov and V. Peskov, "Cs based photocathodes for gaseous detectors," *Nucl. Instrum. Meth.*, vol. A348, pp. 269–274, 1994.
[26] E. Shefer *et al.*, "Coated photocathodes for visible photon imaging with gaseous photomultipliers," *Nucl. Instrum. Meth.*, vol. A433, pp. 502–506, 1999.
[27] A. Bondar *et al.*, "Two-phase argon and xenon avalanche detectors based on gas electron multipliers," *Nucl. Instrum. Meth.*, vol. A556, pp. 273–280, 2006.
[28] L. Periale *et al.*, "A study of the operation of especially designed photsensitive gaseous detectors at cryogenic temperatures," *Nucl. Instrum. Meth.*, vol. A567, pp. 381–385, 2006.
[29] L. Periale *et al.*, "The successful operation of hole-type gaseous detectors at cryogenic temperatures," *IEEE Trans. Nucl. Sci.*, vol. 52, no. 4, pp. 927–931, Aug. 2005.
[30] K. Saito *et al.*, "Absolute number of scintillation photons emitted by alpha particles in rare gases," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 4, pt. 1, pp. 1674–1680, Aug. 2002.
[31] R. Chandrasekharan, M. Messina, and A. Rubbia, "Detection of VUV light at high quantum efficiency with large area avalanche photodiooes (LAAPDs)," *Nucl. Instrum. Meth.*, vol. A567, pp. 45–47, 2006.
[32] J. M. Bidault, "A novel UV sensitive detector with resistive electrodes," *Nucl. Phys. B (Proceedings Supplement)*, vol. 158, pp. 199–203, 2006.
[33] R. Oliviera *et al.*, "First tests of thick GEM with electrodes made of resistive Kapton," *Physics preprint 0701154*, pp. 1–10, 2007.
[34] V. Peskov, B. Ramsey, and P. Fonte, "Surface streamer breakdown mechanism in microstrip gas counters," *Nucl. Instrum. Meth.*, vol. A392, pp. 89–93, 1997.
[35] V. Peskov *et al.*, "Feedback and breakdowns in microstrip gas counters," *Nucl. Instrum. Meth.*, vol. A397, pp. 243–260, 1997.
[36] K. Uglig, *Surface discharges in high magnetic fields*. Konstanz, Germany: Hantung-Gorre Verlag, 1995, pp. 1–314.
[37] C. Iacobaeus *et al.*, "A novel portal imaging device for advanced radiation therapy," *IEEE Trans. Nucl. Sci.*, vol. 48, no. 4, pt. 2, pp. 1496–1502, Aug. 2001.