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# Employment of nanodiamond photocathodes on MPGD-based HEP detector at the future EIC

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**Abstract.** In high momenta range, the construction of a Ring Imaging CHerenkov (RICH) detector for the particle identification at the future Electron Ion Collider (EIC) is a complicated task. A compact collider setup imposes to construct a RICH with a short radiator length, hence limiting the number of photons. The number of photons can be increase by choosing to work in far UV region. However, as standard fused-silica windows are opaque below 165 nm, therefore, a windowless RICH approach could be a possible choice. In the far UV range, CsI is a widely used photo-cathode (PC) to detect photons, but because of its hygroscopic nature, it is very delicate to handle. Its Quantum Efficiency (QE) degrades in high intensity ion fluxes. These are the key reasons to search a novel, less delicate PC with sensitivity in the far UV region. Hydrogenated nanodiamond films are proposed as an alternative PC material and shown to have promising characteristics. The performance of nanodiamond PC coupled to THGEM-based detectors is the objects of our ongoing R & D.

The first phase of these studies includes the characterization of THGEMs coated with nanodiamont PC, the comparison of the effective QE in vacuum and in gaseous atmospheres, the hardness respect to the PC bombardment by ions from the multiplication process. The approach is described in detail as well as all the results obtained so far with these exploratory studies.

## 1. Introduction

The future Electron Ion Collider (EIC) [2] facility will explore quantum chromodynamics (QCD), together with elusive non-perturbative effects and their fundamental unsolved mystery since a long time, such as the origin of nucleon mass, spin and the properties of dense gluon systems. In order to explore these fundamental mystery at EIC, demands an efficient hadron Particle IDentification (PID) sensitive in a wide momentum range, specially it is very much challenging

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at high momenta (for example more than 6-8 $GeV/c$). A gaseous Ring Imaging CHerenkov (RICH) is the only possible choice at such a high momenta.

The number of generated Cherenkov photons in a light radiator is limited, which can be increased with long radiators. However, due to compact design of future EIC, the radiator length is limited. The possible solution is to choose the Photon Detectors (PDs), which is sensitive in the far UltraViolet (UV) spectral region ($\lambda =$ $\sim$ 120 nm), where, the number of generated Cherenkov photon increases, according to the Frank-Tamm distribution [3]. However, as the standard fused-silica windows are opaque below 165 nm, a windowless RICH is a alternative option. The approach also points to the use of gaseous photon detectors operated with the radiator gas itself [4].

The MicroPattern Gaseous Detector (MPGD)-based PDs have recently been reported as a very effective devices [5] even for single photon detection in Cherenkov imaging counters. These PDs are composed of a hybrid structure, where two layers of THick GEM (THGEM) [6] are followed by a MICRO-MEsh GAseous Structure (MICROMEGAS) [7] stage; the top layer of the first THGEM is coated with a reflective CsI PhotoCathode (PC).

CsI is the most used PC in the VUV spectral range since last two decades because of its high Quantum Efficiency (QE) and robustness among alkali halide for gaseous detectors a well as vacuum-based detectors [8], although, because of its hygroscopic nature QE degrades with exposure to humidity [9]. Therefore, CsI PC handling is a very delicate operation. CsI PC QE also degrades with ion bombardment on it, when the integrated charge is 1 $mC/cm^2$ [10] or larger. In gaseous detectors, ion bombardment on PC layers is caused by the ion avalanche produced in the multiplication process. The fraction of ions reaching the cathode depends on the detector architecture. In recent years, MPGD schemes with enhanced ion blocking capability have been developed [5, 11].

The digging for an alternative VUV sensitive PC overcoming the limitations mentioned above is therefore an important objective for the research and development (R&D) program for the experiments at the EIC. In the present article, we have shown the preliminary results on NanoDiamond (ND) and Hydrogenated-NanoDiamond (H-ND) coated THGEM detectors. They also include preliminary results about QE robustness respect to ion bombardment.

## 2. ND powder as a replacement of CsI

In the VUV spectral range CsI PC is mostly used photoconverter because of its high QE. This high QE value is related to its low electron affinity (0.1 $eV$) and wide band gap (6.2 $eV$) [12]. The ND particles have a comparable band gap of 5.5 $eV$ and low electron affinity of 0.35-0.50 $eV$. ND hydrogenation lowers the electron affinity to -1.27 $eV$. The Negative Electron Affinity (NEA) allows an efficient escape into vacuum of the generated photoelectrons without an energy barrier at the surface [13]. A novel ND hydrogenation procedure, developed in Bari [13, 14], provides high and stable QE together with chemical inertness and radiation hardness. A comparison of CsI and ND QE can be extracted from literature [13, 15].

## 3. The R&D activity and results

### *3.1. THGEM characterization before coating*

In the nitial phase of our R&D studies we coated five THGEMs with ND and H-ND powder. THGEMs are robust gaseous electron multipliers can be obtained via standard PCB drilling and etching processes. A 35 $\mu$m copper layer is coated with $\approx$5 $\mu$m of Ni, followed by 200 nm Au. The THGEMs used for our studies have an active area of $30 \times 30$ $mm^2$ with a hole diameter of 0.4 mm, a pitch of 0.8 mm and a thickness of 470 $\mu$m. THGEMs with different rim (clearance ring around the hole edge), have been used: $\leq 5\mu$m (no rim), $\sim 10$ $\mu$m and $\sim 20$ $\mu$m.

Each THGEM is characterized in a small aluminium chamber as shown in top & bottom image (left panel) of figure 1. The straight drift wires on the top THGEM and a segmented

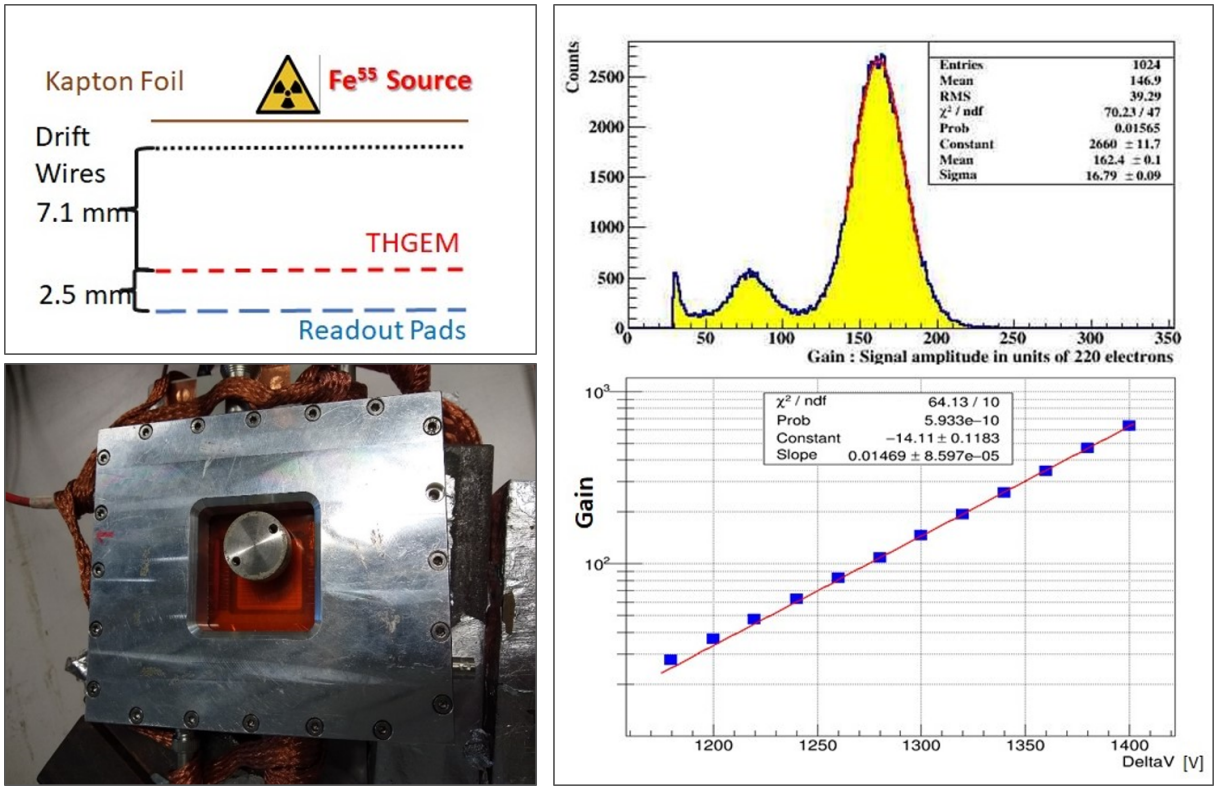


**Figure 1.** Top-left panel: The schematic of our detector assembly. Bottom-left panel: The detector is illuminated with an $^{55}Fe$ X-ray source . Top-right panel: A typical $^{55}Fe$ X-ray spectrum obtained in $Ar : CO_2 = 70 : 30$ gas mixture when the applied voltages at drift, top and bottom of THGEM are -2520 V, -1720 V and -500 V respectively, while the anode is at ground. Bottom-right panel: shows the gain dependence of the THGEM versus the applied voltage.

readout pads below the THGEM are properly biased in order to provide the drift and induction field respectively. Various gas mixtures are used for the THGEM characterization, for example $Ar : CO_2 = 70 : 30$. The electrons from $^{55}Fe$ X-ray source converted by Ar are collected and multiplied in the hole region of the THGEM. The electron avalanche generated in the multiplication process, while drifting towards the anode, results the detected signal.

All above mentioned THGEMs used for our studies have been characterized using different gas mixtures at INFN Trieste before applying coating. The purpose is to perform comparative studies after coating them with UV sensitive layers.

A typical $^{55}Fe$ X-ray spectrum obtained in $Ar : CO_2 = 70 : 30$ gas mixture is shown in figure 1, top-right panel. The bottom right panel of figure 1 shows the gain dependence of THGEM versus the voltages applied across it.

### *3.2. ND and CsI coating details*

THGEMs have been coated with raw ND power solution, namely as-received powder or with hydrogenated ND (H-ND). ND powder with an average grain size of 250 nm produced by Diamonds & Tools srl has been employed. The coating is performed on one side THGEM of either the whole surface or half surface.

The standard procedure of hydrogenation of ND powder photocathodes is performed by using a MicroWave Plasma Enhanced Chemical Vapor Deposition (MWPECVD) technique. For the

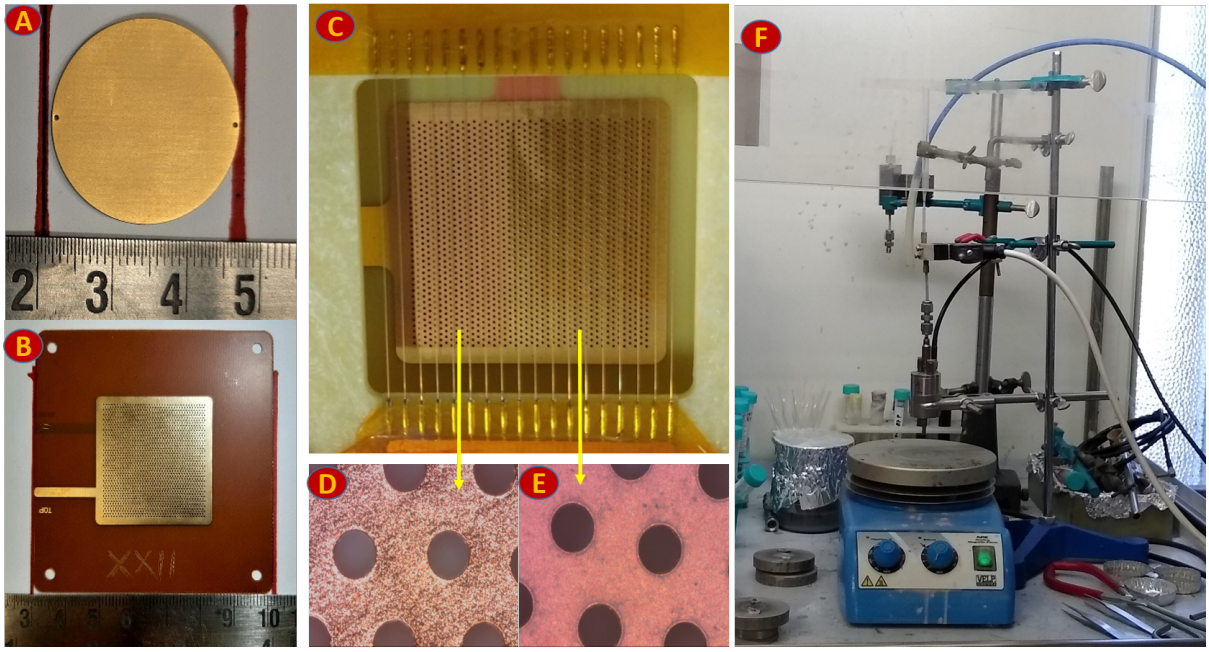


**Figure 2.** (A) Au_PCB of 1 inch diameter substrate used for the QE measurement. (B) Uncoated THGEM of active area 30 mm×30 mm. (C) Half uncoated and half coated THGEM, mounted into the test chamber and zoomed view of the both coated (D) and uncoated (E) part. (F) a pulsed spray coating setup at INFN Bari, Bari-Italy.

treatment in microwave (mw) $H_2$ plasma, 30 mg of ND powder were placed in a tungsten boat (overall length 32 mm, trough 12 mm long 5 mm wide 1 mm deep, Agar Scientific Ltd) positioned on a heatable substrate holder of an ASTeX-type reactor evacuated to a base pressure better than $7 \times 10^{-7}$ mbar. The powder was heated to $650^0$C using an external radiative heater (via a Proportional-Integral-Derivative feedback control system), then $H_2$ gas was flowed in the chamber at 200 sccm, the pressure and the mw power were maintained at 50 mbar and 1250 W, respectively. The heating due to the mw power increases further the temperature of the powders up to $1138^0$C as determined by a dual wavelength ($\lambda 1 = 2.1\ \mu m$ and $\lambda 2 = 2.4\ \mu m$) infrared pyrometer (Williamson Pro 9240). After 1 h of $H_2$ plasma exposure, the hydrogenated powder were cooled to room temperature under high vacuum. This procedure can not be used for THGEMs which are made by fiberglass, which does not tolerate temperatures above $180^0$C.

This problem is solved by the novel and low-cost pulsed spray technique developed at INFN Bari [16, 17]. The H-ND is obtained by treating the as-received powder in $H_2$ microwave plasma for one hour before deposition.

The ND and H-ND powder were separately dispersed in deionized water and sonicated for 30 minutes by a Bandelin Sonoplus HD2070 system. Then, the emulsion was sprayed on the THGEM and on Au coated PCB coins at $120^0$C or slightly higher temperature.

Four THGEMs with different geometrical characteristics have been coated as listed below:

- 0 $\mu m$ rim - ND half coated
- 0 $\mu m$ rim - H-ND half coated
- 10 $\mu m$ rim - H-ND full coated
- 20 $\mu m$ rim - ND half coated

A fifth THGEM with 10 $\mu m$ rim was coated with a reflective CsI film by thermal evaporation technique at INFN Bari.

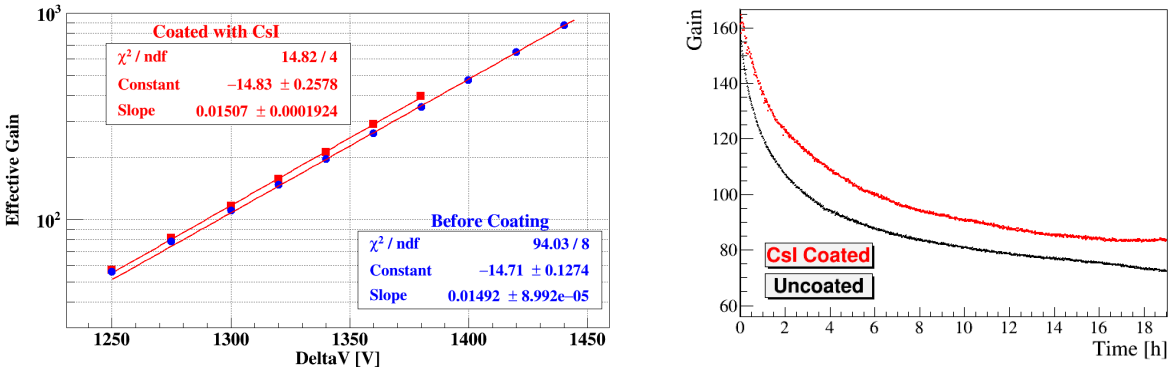


**Figure 3.** The gain of the THGEM with 10 $\mu$m rim measured before and after CsI coating are compared. Left panel: Gain versus applied voltage across the THGEM electrodes. Right panel: gain evolution versus time.

Coated substrates together with the pulsed spray coating unit are shown in Fig. 2.

*3.3. THGEM characterization after coating*

THGEMs characterization after CsI, ND and H-ND coating depicts very interesting results in comparison with uncoated THGEM.

The THGEM gain in all three cases of coating are found to be higher than uncoated THGEM. However, this increase in gain for the coated part depends on the coating materials as well as on rim size.

The THGEM with $\sim$ 10 $\mu$m rim size, coated with a reflective CsI showed a 20% gain increment in comparison to the uncoated ones as shown in Fig. 3.

A possible explanation of the observed gain increase is the lower rate of charging-up of the free dielectric surface. The surface resistivity is decreased with the coating, due to the coated material resistivity.

The left panel of Fig. 4, shows $^{55}Fe$ X-ray spectra obtained for both uncoated and ND coated parts of the THGEM with $\sim$ 20 $\mu$m rim size. The voltages applied to drift, top and bottom of the THGEM electrodes are 3510 V, 2110 V and 750 V respectively. The gain of the ND coated part is $\approx$ 2 times higher compared to the one of the uncoated part.

In case of a ND coated THGEM with no rim the gain of the coated part is larger by a factor of $\sim$1.4 as shown in Fig.5 left panel. The gain is maximum when the X-ray source starts illuminating and it decreases gradually by $\sim$ 20% in about 08 hours. This effect is observed for both ND coated and uncoated THGEM parts as illustrated in Fig.5, right panel.

The possible explanation of the increase in gain is the same one already proposed for the gain increase observed with CsI coating. The increase is higher when the open dielectric surface is larger, namely for the $\sim$ 20 $\mu$m rim THGEM.

The H-ND coated THGEMs with 0 $\mu m$ and 10 $\mu m$ rim show a lower electrical stability as compared to the uncoated THGEMs and cannot be operated at nominal voltage. In order to study this unexpected behaviour a second exercise was performed using a new THGEM with no rim fully coated with H-ND and in $Ar : CH_4 = 50 : 50$ gas mixture. For the H-ND coating we used same emulsion which is prepared 17 months before and was kept in normal atmosphere. Immediately after the coating the THGEM could not be operated at the nominal voltage. A heat treatment in an electric oven at 120 $^0C$ for 24 hours solve this electrical instability problem and allowed to perform the characterization. The right panel of figure 4 shows the signal amplitude distributions measured before and after the H-ND coating followed by the heat treatment. No

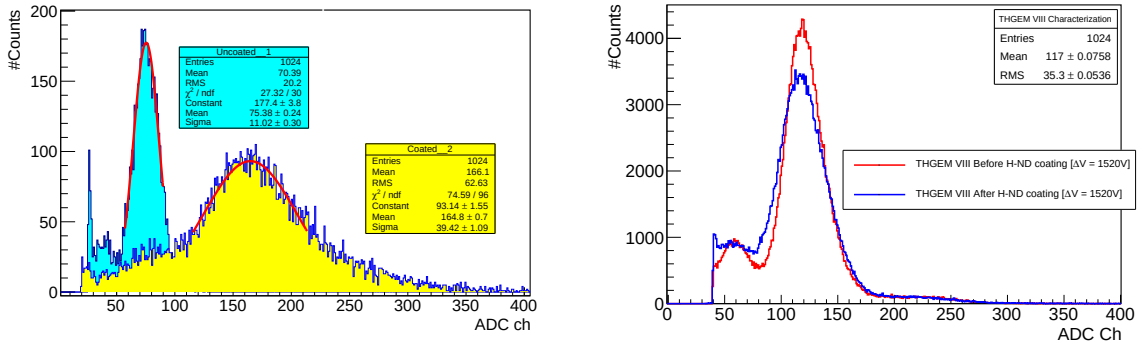


**Figure 4.** Left panel: $^{55}Fe$ X-ray spectra obtained with a 20 $\mu$m rim THGEM half-coated with ND powder in $Ar : CO_2 = 70 : 30$ gas mixture. The voltages applied to drift, top and bottom of the THGEM electrodes are 3510 V, 2110 V and 750 V respectively, while the anode is kept at ground. Right panel: $^{55}Fe$ X-ray spectra obtained with a 0 $\mu$m rim uncoated THGEM. The same measurement after coating the same THGEM with a H-ND emulsion prepared 17 months earlier in a $Ar : CH_4 = 50 : 50$ gas mixture

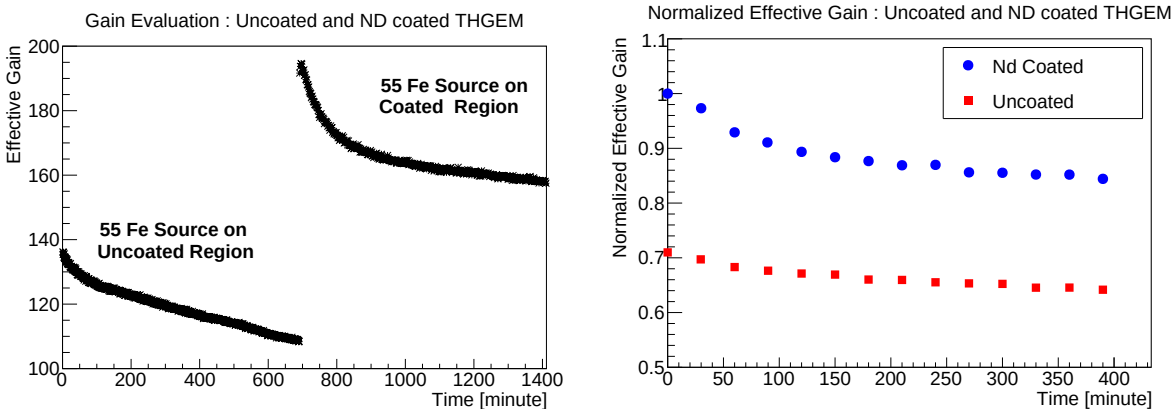


**Figure 5.** Evolution versus time of the effective gain behavior of a THGEM with 0 $\mu$m rim, half-coated with ND. Gain versus time (left panel); the source is moved to the coated region at $\sim$ 11.33 hours. The same data normalized to the maximum gain measured in the coating region versus time, where t=0 is when the illumination of a region starts (right panel).

evidence for increase of gain is observed. This observation suggests that the electrical instability present before the heat treatment can be related to water molecules present at the H-ND surface.

A consistent picture is emerging in spite of the initially unexpected results obtained characterising the coated THGEMs. The consolidation of this picture requires further investigation.

### *3.4. Ageing exercise of H-ND PC*

QE measurements can be performed with the available VUV monochromator only in case of small-size samples. Therefore, the same coating procedure used for the THGEM samples has been applied to PCB coin substrates of one inch diameter. The PCB coin material and surface preparation are the same of the THGEMs, even if no hole structure is present (Fig. 2 A). The H-ND coating applied is with an emulsion of 17 months old hydrogenated ND powder.

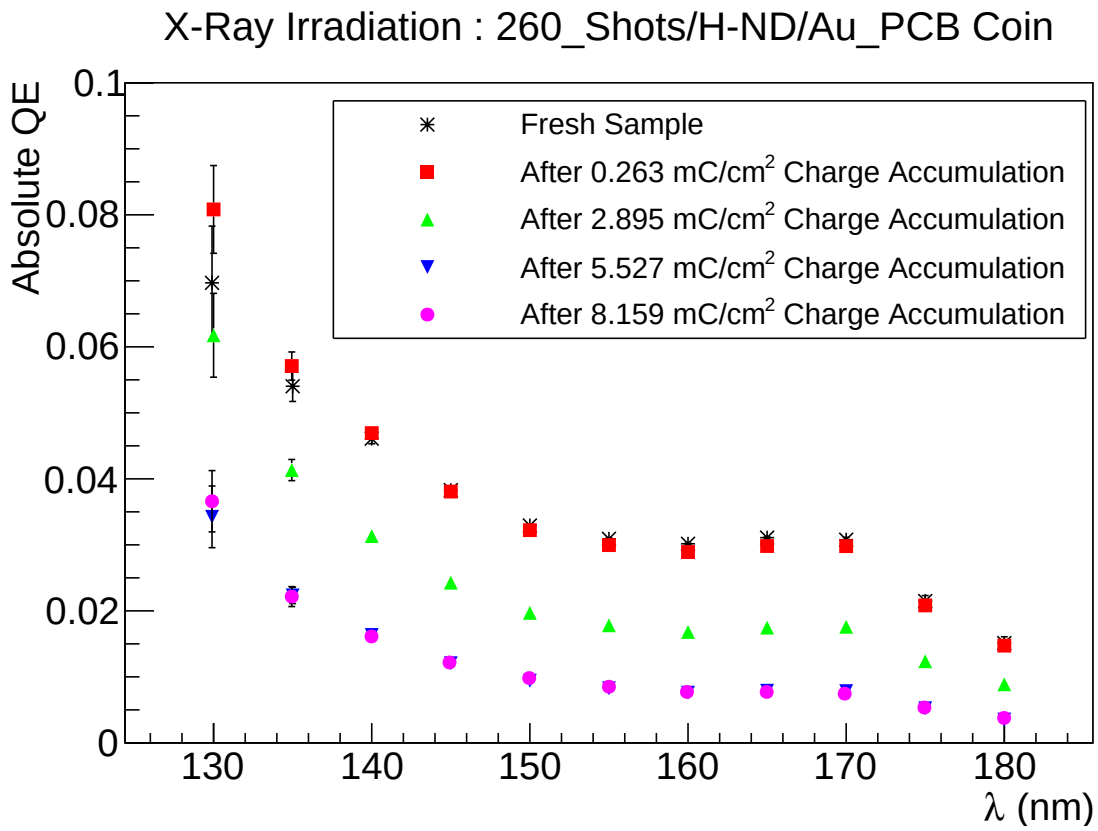


**Figure 6.** Quantum efficiency as a function of wavelength for fresh and various charge accumulations ($0.263 mC/cm^2$, $2.895 mC/cm^2$, $5.527 mC/cm^2 and$ $8.159 mC/cm^2$) due to ion bombardment on H-ND coated Au_PCB substrate.

For the QE measurement a McPherson VUV monochromator (model 234/302) was employed at RD-51 lab CERN, known as ASSET system [18]. For the ageing study a H-ND coated PCB coin was irradiated with a mini X-ray source in $Ar : CO_2 = 70 : 30$ gas mixture. In this ASSET system both the QE measurement and ion bombardment can be performed in situ without exposure to air. Ions are generated by a gaseous multiplier metallic grid set fixed 5 mm above from the coin surface and they impinge on the sample surface. The QE of an H-ND coated coin was measured before irradiation in a wavelength range from 130 nm to 180 nm with a scan step of 5 nm. The sample was then moved to the X-ray irradiation chamber using an automated manipulator under vacuum ($\approx 1 \times 10^{-7} mbar$). The QE has been measured again after controlled doses of accumulated charge and the measurements are reported in Fig. 6.

The QE before ion bombardment and after an accumulated charge of $0.263 mC/cm^2$ are similar in whole wavelength range. This strongly supports the hypothesis that H-ND PC are more robust than CsI PC in terms of ion bombardment. In fact, in case of a CsI photocathode, a 25% drop in QE is observed for an irradiation of $1.0 mC/cm^2$ [10].

For the H-ND coated sample, a decrease in the QE of 42% and 74% was observed as charge accumulation reached the values of $2.895 mC/cm^2$ and $5.527 mC/cm^2$, respectively. Interestingly, we did not observe any further degradation in the QE for an accumulated charge of $8.159 mC/cm^2$. This is the first preliminary irradiation ageing study of H-ND PC ever performed.

## 4. Conclusion

THGEM samples were deposited with different types of photosensitive layers (CsI, ND and H-ND) and have been studied. An increase in the gain response for the CsI and ND coated THGEMs was observed compared to the uncoated ones. The electrical instability of the H-ND coated THGEM, initially observed, is overcome by a heat treatment. No gain enhancement is observed.

The X-ray irradiation study on H-ND photocathodes performed by us for the first time indicates that H-ND is more robust than CsI. We can conclude that H-ND photocathode material is a promising alternative to CsI based photocathodes for all applications in the far VUV domain requiring high robustness.

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