

# Photocathode Characterisation Setup Development and Testing

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## Abstract

This project was conducted within the Gas Detectors Development (GDD) group at CERN. The main goal was to build a setup that will allow photocathode characterisation and ageing effects measurements. The setup built allowed the irradiation of photocathodes with different wavelengths, from 110 nm to 250 nm, and supported an ion irradiation chamber to study ageing effects. The results show the expected wavelength-dependent quantum efficiency of CsI photocathodes but they do not represent absolute values due to issues while assembling the setup. When the setup is completed, absolute values of the photocathodes' quantum efficiencies and a full comprehension of the effects of the overtime use of photocathodes will be possible to study.

## 1 Introduction

This project emerges within the PICOSEC collaboration, which aims at developing a precise timing detector based on Micromegas (micro mesh gaseous detector). The group has developed a prototype detector which is a combination of a Cherenkov-radiator, a photocathode and a MicroMegas for signal amplification. With this detector, the results achieved were sub 50-picosecond time resolutions, in 2017 during multiple SPS (super proton synchrotron) test beams campaigns. This time resolution is a novelty in the field of gaseous detectors for the studies of charged particle timing at high rates.

The upcoming HL-LHC (high luminosity - large hadron collider) project has shown great interest in these studies since this presents, possibly, a solution for the existing pileup problem. [1]

Besides scaling up to larger areas, initiatives for finding more robust photocathodes are currently ongoing within the PICOSEC collaboration. In this matter, this project also intends to evaluate the long term stability of photocathodes as the usual CsI photocathodes experience significant ion fluxes which result in the deterioration of their quantum efficiencies and therefore decreased lifetimes. In order to scrutinise and minimise this issue, a photocathode characterisation setup was needed.

Within this project, and with the help of my supervisors Dr. Florian Brunbauer and Dr. Leszek Ropelewski and the rest of the group, I focused my work in the development, assembly and calibration of a photocathode characterisation setup. This setup is designed to permit the study of photocathodes' quantum efficiencies and ageing effects. The setup will also be used to investigate possible protection layers and their effect on the ageing behaviour and quantum efficiency of photocathodes.

Over the course of this project, a vacuum chamber (including pumps, gauges, valves, etc.) was built; a system that includes a light source together with a monochromator and optical components was installed, and light detection devices, instrument control and data acquisition software were used.

## 2 Theory

### 2.1 Photocathode

A photocathode is a layer from which electrons are extracted under the irradiation with light. Its main purpose is to create free electrons when struck by photons due to the photoelectric effect. Some photocathodes such as CsI layers are sensitive to air and operate in vacuum in behalf of that.

Photocathodes can work in two different configurations: transmission and reflection. In the first case, the electrons exit the photocathodes from the opposite surface where the light enters and, in the second case, the electrons exit from the same side.

The most important feature of a photocathode is its quantum efficiency. Quantum efficiency of a photocathode is defined as the ratio of the incident photons to the freed electrons, as shown in Eq. (1):

$$QE = \frac{N_{e^-}}{N_{ph}} \quad (1)$$

where  $N_{e^-}$  is the number of freed electrons and  $N_{ph}$  is the number of incident photons.

Photocathodes usually have a quantum efficiency of 30% at 150 nm [2] but the values are strongly dependent on their composition. Photocathodes' quantum efficiencies are also very wavelength dependent as different photocathodes are sensitive to different light spectra. The sensitive wavelengths can go from 100 nm (if they are composed of CsI [2], for example) up to 1700 nm (if they are made of InGaAs [3]). One can also cover a photocathode with a proper coating in order to improve its efficiency, for example, NaF protective films [4].

The study of photocathodes are of great interest for a wide range of detectors. For instance, PMTs (photomultiplier tubes), as photocathodes can convert light into electrons thus providing a collectable signal for processing and later analysis. Gaseous detectors in general also use photocathodes for the same reason.

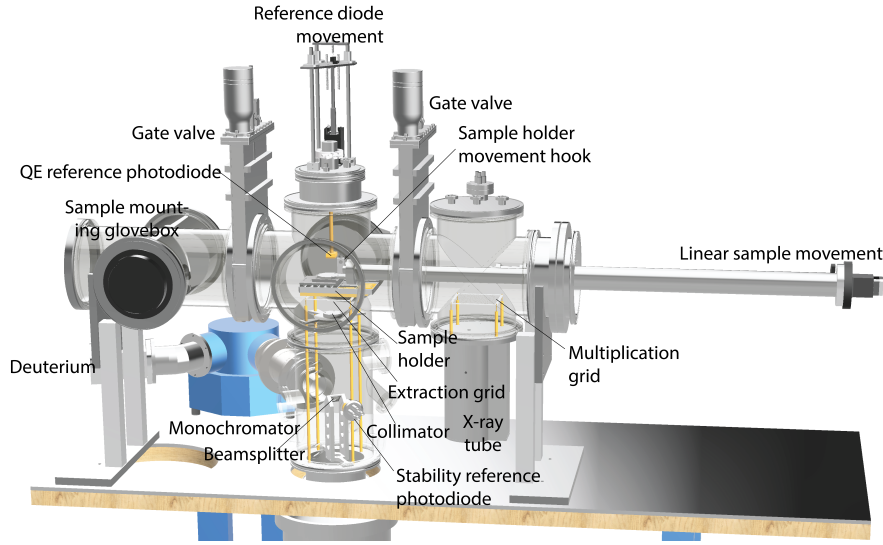
## 3 Setup

In this project, the photocathodes used were composed of a 3mm  $\text{MgF}_2$  substrate, 3 nm Cr layer on top of  $\text{MgF}_2$  and 18 nm thick transparent CsI on top of that. The reason for this is that the characteristic Cherenkov Light's wavelengths are below 200 nm and the CsI photocathodes are optimal in this region. It is also important to note that this type of photocathode is, in general, easier to handle, comparing to Bi-alkali photocathodes.

The measurements were done under high vacuum regime, where the pressure is about  $3 \times 10^{-7}$  to  $8 \times 10^{-7}$  mbar. This is related with the quantum efficiency's range of interest (110-200 nm) as air starts to cut radiation at, approximately, 200 nm.

The vacuum system had a small pre-vacuum pump that provided pressures in the order of  $10^{-3}$  mbar. It also had a strong turbomolecular pump which allowed to work with pressures in the order of  $10^{-7}$  mbar. To avoid contamination, all the materials inside the chambers were cleaned before being used with an alcohol ultra-sonic bath. Alcohol tests were also performed for all the connections to ensure that there were not any leaks.

The setup (shown in figure (1)) assembly was divided in three big parts: setting up and preparing the beam that would irradiate the photocathodes; measuring currents from photodiodes to calculate the photocathodes' quantum efficiencies, and designing a software capable of controlling all the setup's moving parts and suited to recording all the data acquired.

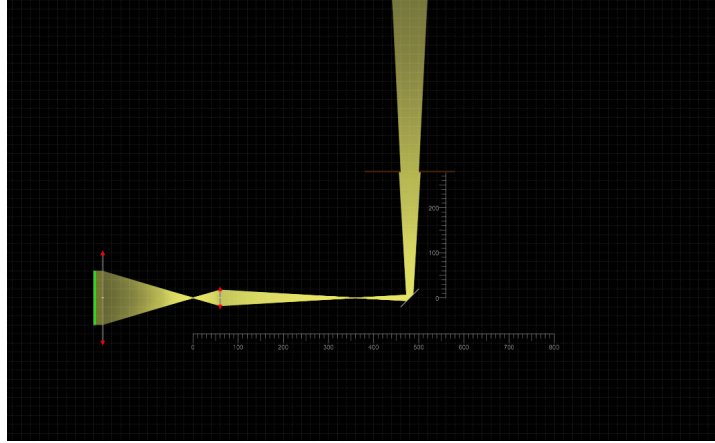


**Figure 1:** 3D model of the full setup.

### 3.1 Beam

The beam setup had 5 important parts:

- **Light Source**  
30W emission from a deuterium lamp with a  $\text{MgF}_2$  window and a wavelength range of 115 nm to 380 nm. (*McPherson*, model 632.) [5]
- **Monochromator**  
The monochromator was used to select one specific wavelength and it was operated under  $\text{N}_2$  flushing as air is opaque to wavelengths superior to  $\approx 200$  nm. (*McPherson*, model 234/302.) [6]
- **Lens**  
A  $\text{CaF}_2$  lens followed the monochromator in order to focus the beam into the beam splitter. In figure (2), it is shown a simulation of the intended beam focus.



**Figure 2:** Rough estimation of how the beam should behave.

- **Beam splitter**  
Metallic layer on 1-inch substrate used as beamsplitter with about (30-40) % reflectance and transmission.  
The beam splitter was used to couple a part of the incident UV light beam to a reference photodiode for intensity stability monitoring during the measurements, and the other part to the samples (photocathodes).
- **Collimator**  
The collimator was not used in the presented measurements.  
Before hitting the photocathodes, the beam would go through it so the beam could hit only a small region of the photocathodes.

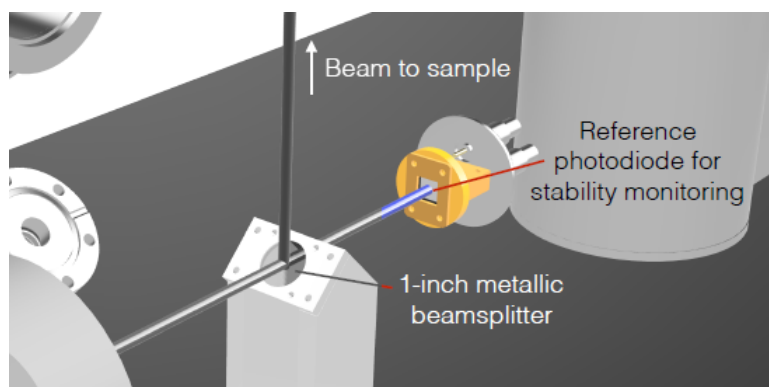
## 3.2 Quantum efficiency measurement

### 3.2.1 Current extraction

The current of electrons extracted from the photocathode was collected by a mesh placed under the samples and biased positively. To compensate for the electrons released by photoelectric effect, the photocathode creates a current and, since the samples were grounded and connected to a picoammeter, this current can be measured. The biased mesh served as a collecting grid.

### 3.2.2 Stability monitoring measurement photodiode

To monitor the beam and its stability, a photodiode was mounted in front of the beam splitter. Due to the beam splitter's position, this photodiode always sees the beam. This measurement is important to ensure that the beam's intensity stays consistent during the measurements of the current created by the photocathodes. Figure (3) shows the position where this photodiode was mounted.

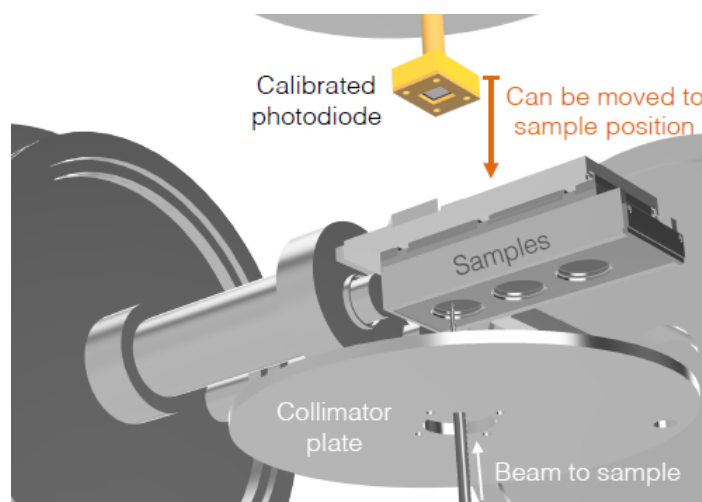


**Figure 3:** Scheme of how the stability monitoring photodiode was mounted.

### 3.2.3 Absolute reference measurement photodiode

After measuring the current generated by the photocathodes, the sample holder (which is mounted on a linear feedthrough controlled with a stepper-motor) is retracted and a photodiode descends to be in the exact same position as the photocathode. With this photodiode it is possible to measure the incident light's intensity that the photocathode received and compare it with the photocurrent produced by the photocathode, thus allowing the calculation of the photocathode's quantum efficiency.

The next figure show a schematic of the photocathode's movement.



**Figure 4:** Scheme of how the absolute reference measurement photodiode moves.

## 3.3 Glovebox and ion irradiation chambers

These two chambers were not mounted due to time constraints and delays in the delivery of important components.

The glovebox would serve the purpose of allowing the samples' insertion and exchange without exposing them to air and also avoiding the exposure of the main chamber.

The irradiation chamber would allow a study of ion bombardment-induced ageing effects, in the following way: a X-ray light would irradiate the chamber now full

with gas and, with a mesh working as multiplication grid, the gas' freed electrons would be pulled towards the mesh and the ions would go towards the samples (ion bombardment).

### 3.4 Automation

The movement of several components of the setup was controlled with the Arduino and Labview softwares in order to provide us and the community with the possibility of an easy to use, intuitive and reproducible remote control and data acquisition system. (Appendix A)

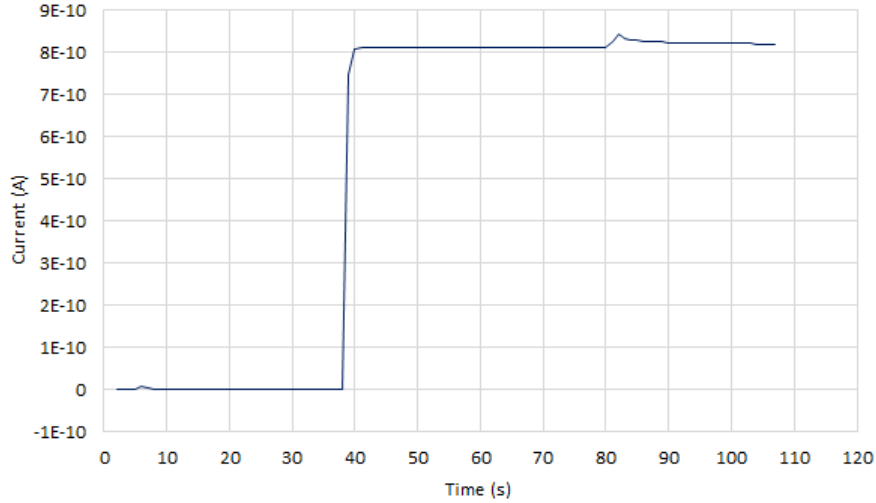
This system also allowed repetitive and automatic measurements (which are, in order: measure the photocurrent at a specific wavelength; repeat for different wavelengths; irradiate the samples with ions; repeat the measurements in the same wavelengths).

In particular, this system controlled and acquired information from: one linear motor; one stepper motor (which was used to move the linear feedthrough holding the samples); two photodiodes; three photocathode samples; one monochromator; two pressure gauges and a high voltage module.

## 4 Tests

### 4.1 Light source

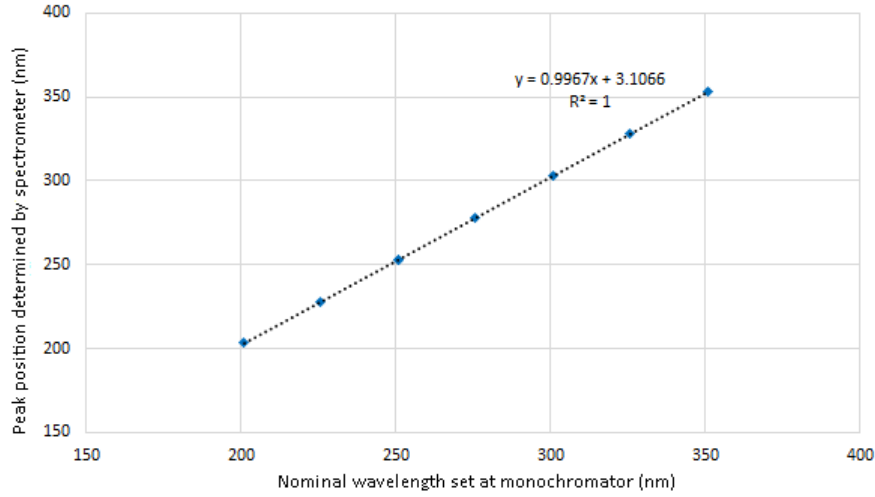
It is important to monitor the stability of the light source. Figure (5) shows the current extracted with the photodiode in front of the beam splitter at 150 nm.



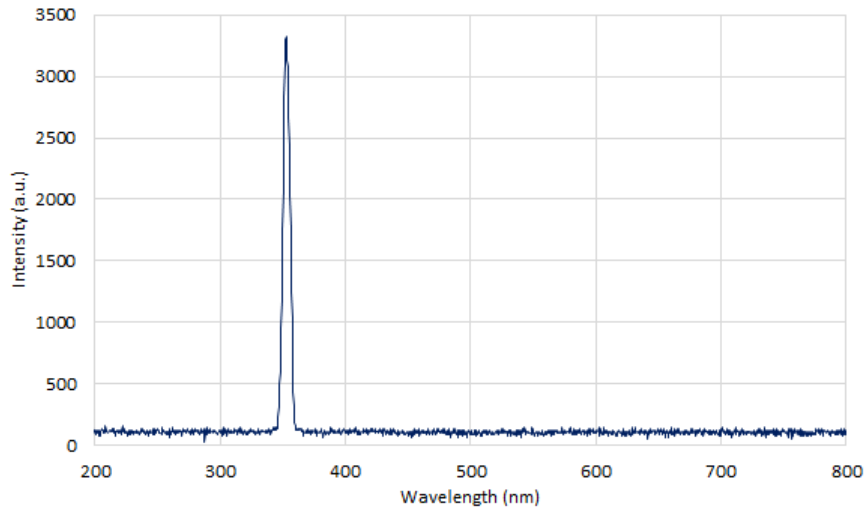
**Figure 5:** The light turns on on second 39. The jump seen after 45 seconds appears because the light source turns off the heating mechanism.

## 4.2 Monochromator

To test the monochromator's accuracy and precision, a compact CCD-based spectrometer with a wavelength range of 200-800 nm was used: The procedure involved comparing the wavelength Gaussian peaks obtained with the spectrometer with wavelengths that the monochromator was showing. The next graphs show the results obtained.



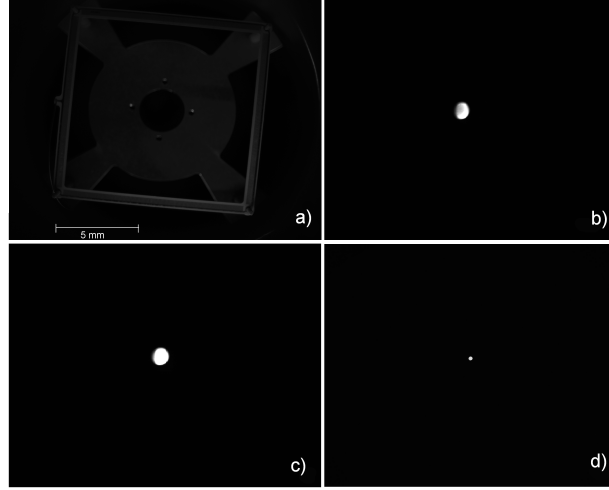
**Figure 6:** The monochromator has a good linearity, but has an offset of roughly 3 nm.



**Figure 7:** We can identify a FWHM (Full Width at Half Maximum) of roughly 5 nm at 350 nm, with the entrance and exit slits of the monochromator fully open with a 3 mm slit width.

### 4.3 Lens, beam splitter and collimator

With these five items in position, a camera was placed in line with the beam splitter and the collimator to monitor alignment adjustments and ensure that the beam was focused and aligned. The next figure shows the alignment process:



**Figure 8:** Here we can see the alignment progress: a) Ambient light; b) Not aligned; c) Aligned; d) Aligned and with a collimator.

### 4.4 Mesh stability

The following tests were run to verify if there were any current leak and/or sparks on the mesh under the samples which would later help to extract the current from the them. In this case, the stability criterion was having a leakage current below  $\approx 10 \mu\text{A}$ .

| Pressure (mbar)    | Voltage (V) | Stability |
|--------------------|-------------|-----------|
| 1020               | 1000        | ✓         |
|                    | 1500        | ✓         |
|                    | 2000        | ✓         |
|                    | 2500        | ✓         |
| $7 \times 10^{-2}$ | 400         | ✓         |
|                    | 465         | ✓         |
|                    | 470         | ✗         |
|                    | 467         | Limit     |
| $2 \times 10^{-5}$ | 400         | ✓         |
|                    | 600         | ✓         |
|                    | 800         | ✓         |
|                    | 1000        | ✓         |
|                    | 1300        | ✓         |
|                    | 1600        | ✓         |
|                    | 2000        | ✓         |

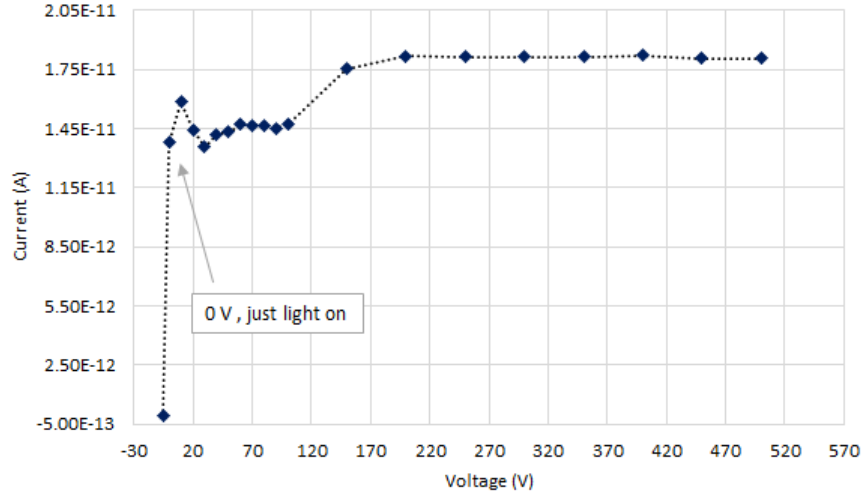
**Table 1:** There were some sparks and current leaks at the  $7 \times 10^{-2}$  mbar pressure but this was not a problem since the measurements were done in high vacuum ( $10^{-6}$  to  $10^{-7}$  mbar).

## 5 Results

### 5.1 Extraction efficiency

To find a suitable electric field to apply between the photocathodes and the mesh that would allow the collection of all the freed electrons, the bias voltage of the mesh was varied from 0 V to 500 V and the collected current was recorded. The distance between the mesh and the photocathodes was 0.5 cm.

The following graph shows the current extracted from the samples while being irradiated with the beam and with the mesh under them at different voltages. This test was performed at 150 nm.



**Figure 9:** A plateau is reached at 200 V, hinting at effective collection at this voltage. We also see that the photocurrent is bigger at 10 V than at 60 V which is a result of the light source's intensity change after being turned on for 45 seconds. This issue is represented because the change on the lamp intensity was noticed only later in the project.

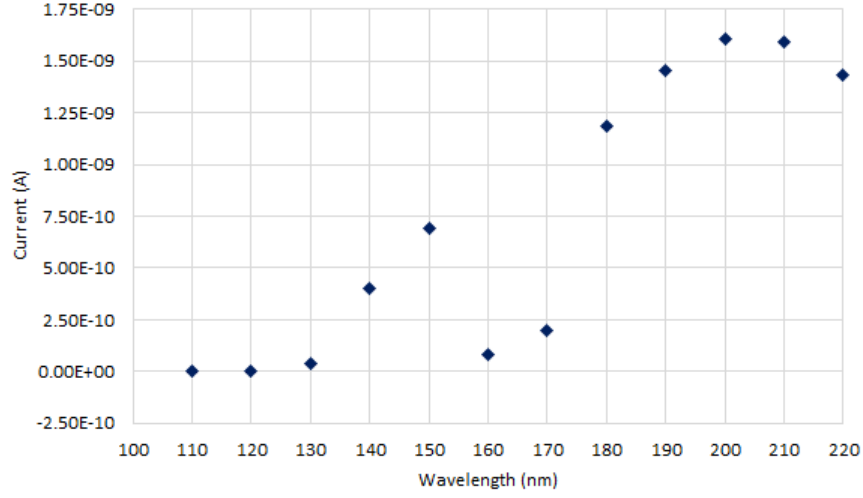
As a result of this, on the posterior tests, the mesh under the samples was biased with +250V.

### 5.2 Quantum efficiency

The photocathodes samples were prepared by M. van Stenis (CERN) for usage in the latest test beam campaign of the PICOSEC detector.

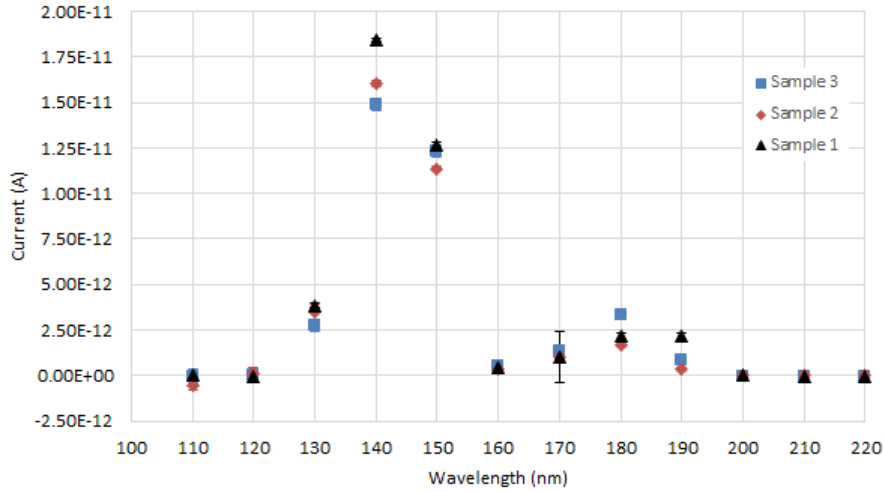
First, one need to know the radiation intensity that reaches the samples. For this, the data acquired by the photodiode located in the front of the beam splitter was used. This was not planned but due to an alignment issue, it was not possible to use the absolute reference measurement photodiode. Instead, the stability monitoring photodiode was used as reference for measurements.

The resulting spectrum is a product of all the absorption/transmission curves of all the components that influence the beam: absorption by nitrogen flushed into the monochromator; CaF<sub>2</sub> window and lens; beam splitter and photodiode response. The following graph shows the results:



**Figure 10:** Current extracted by the stability monitoring photodiode, placed in front of the beam splitter. It is important to note that we have a low peak at 162 nm.

The next procedure was to measure the resulting photocurrents produced by 3 different photocathode samples when struck with the light measured, represented in the next graph.



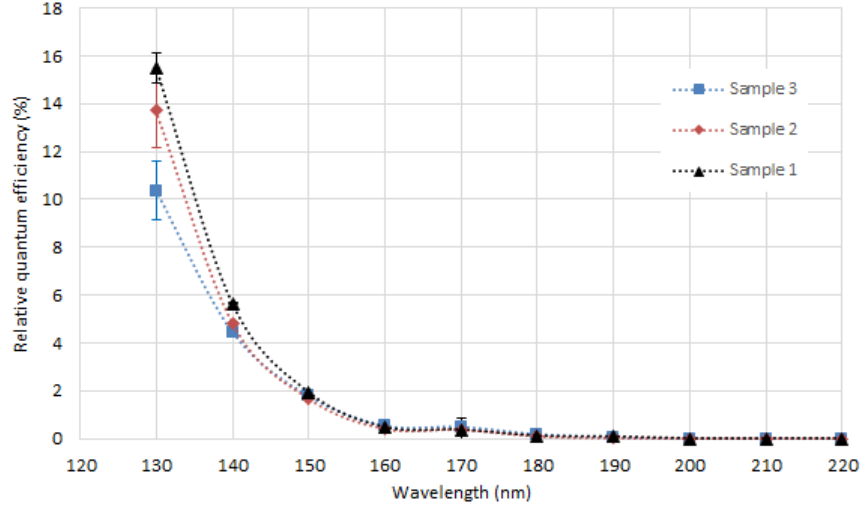
**Figure 11:** Both in this and in the Fig. (10), we can see a low peak at 162 nm. This means that there is something absorbing this particular wavelength. We can also see that, in both graphs, the current intensity below 120 nm is almost zero, which is attributed to absorption by the  $\text{CaF}_2$  lens and window in the beam path.

Then, after correcting the currents given by the photodiode with its own response curve, one can calculate the quantum efficiencies of each photocathode sample. This correction was made by converting the photodiode's responsivity to quantum efficiency of the photodiode, using the following equation:

$$QE_{\lambda} = \frac{R_{\lambda}}{\lambda} \times \frac{hc}{e} \approx \frac{R_{\lambda}}{\lambda} \times (1240 \text{ W} \cdot \text{nm}/\text{A}) \quad (2)$$

with the responsivity  $R_{\lambda}$  in A/W,  $\lambda$  the wavelength in nanometers,  $h$  the Planck constant,  $c$  the speed of light in vacuum and  $e$  the elementary charge.

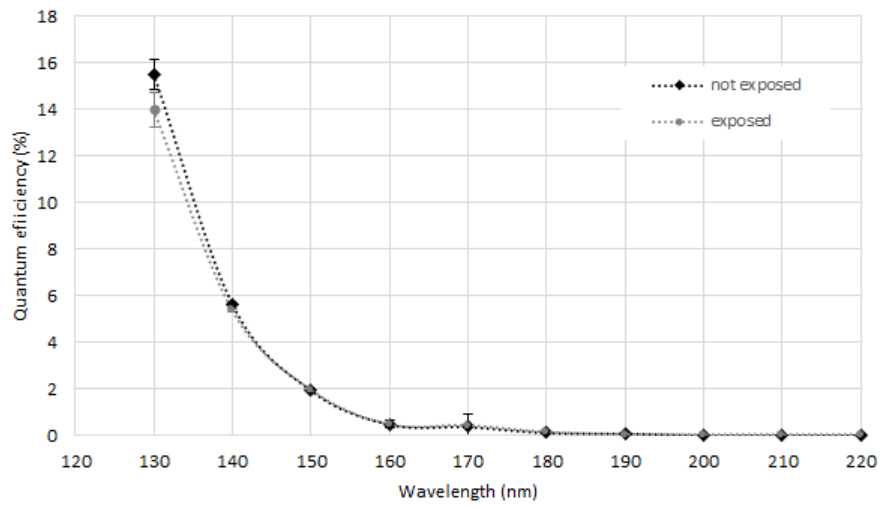
Subsequently, comparing the current measured by the photodiode corrected for the photodiode's quantum efficiency and the photocurrent extracted from the photocathode samples, the quantum efficiency of the samples can be determined. In figure (12), it is shown the results for the quantum efficiency of all the three samples.



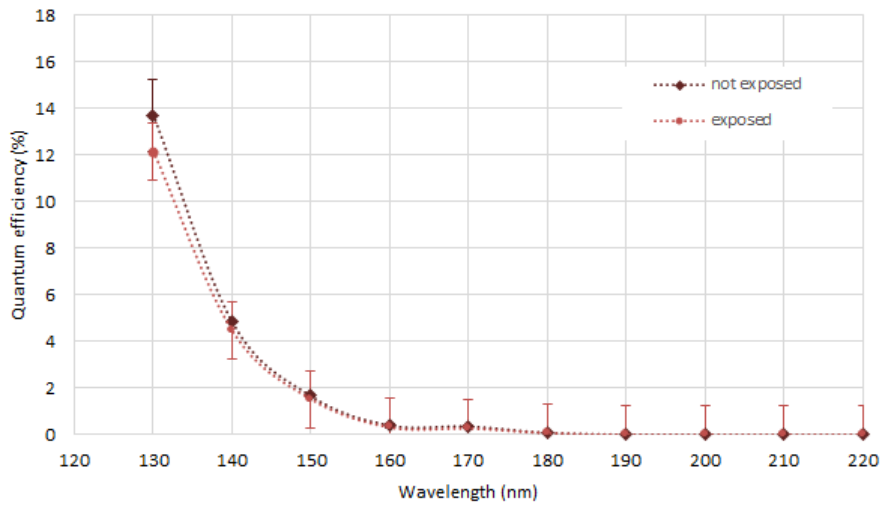
**Figure 12:** The quantum efficiency reduces to zero when we approach 200 nm which indicates the photocathodes become inefficient in this region. It is also important to say that these particular photocathodes should all have roughly the same quantum efficiency since they are similar in composition and usage, which is confirmed by the overlapping points after 150 nm and the big error bars in the first two points, which are due to very low current measurements.

### 5.3 Quantum efficiency degradation

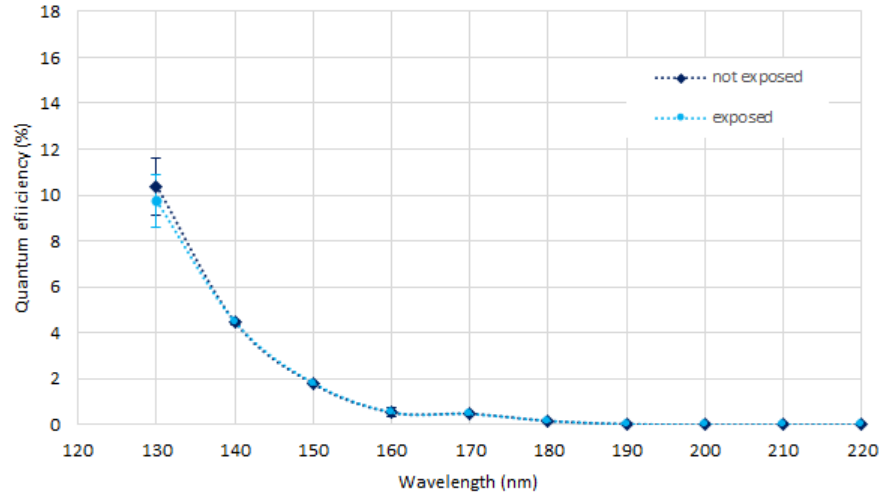
It was not possible to assemble the X-ray tube and use the irradiation chamber within the time allocated for the project. However, it was still possible to make some measurements on the quantum efficiency degradation by exposing the photocathodes to air. The next graphs show the comparison of the photocathodes' quantum efficiencies before and after them being exposed to air.



**Figure 13:** Sample 1 after being exposed to air for 1 hour.



**Figure 14:** Sample 2 after being exposed to air for 1 hour.



**Figure 15:** Sample 3 after being exposed to air for 1 hour.

The error propagation reveals this results are inconclusive. Since, on both measurements, the error bars overlap in the first points, we cannot say that we have a noticeable quantum efficiency degradation which could be attributed to exposure to air.

## 6 Discussion

While doing the beam alignment, we came across several problems regarding the monochromator and lens' positions which resulted in an unsatisfactory beam focus. To mitigate this problem, some manual alignment was needed.

There was still some misalignment in the end, probably due to the beam splitter. This problem will be addressed later as the current setup did not offer enough degrees of freedom in the positioning of beamsplitter and other optical components to permit a reproducible and accurate alignment.

The first measurements obtained from the photodiodes showed very low current levels, as the values would not even reach 1 nA. This was a small problem easily solved by changing the protection resistor connected between the photodiodes and the picoammeter to a value of 100 k $\Omega$ .

Analysing the quantum efficiency measurements we can see that both reference currents and photocurrents have a low value peak near 162 nm. This means that it is not due to the photodiode responsivity but rather something unknown for now. After a careful study of the CaF<sub>2</sub> window, nitrogen and beam splitter absorption spectra and the photodiode responsivity curve, we could not find an outstanding reason to this phenomenon.

The wavelengths of 110 nm and 120 nm are not represented in the quantum efficiency graphs for a similar reason. In this case, it is easy to explain the irregular results. They are a result of the CaF<sub>2</sub> lens and window absorption spectrum which blocks almost entirely the light at this wavelengths. Due to this, the currents extracted are insignificant and float around zero, which usually has as consequence unreasonable values for the quantum efficiencies.

Analysing the quantum efficiencies performances, we can see that the CsI photocathodes become inefficient at wavelengths bigger than 200 nm, as expected. [2].

Even though the quantum efficiency values do not match the literature [2], the behaviour does. We can clearly see the higher value at 130 nm and then a reduction towards 0 % as we approximate to 200 nm.

It is important to note that these values are not absolute because they were not calculated with the absolute reference photodiode due to the beam misalignment. Instead, the stability monitoring photodiode was used and therefore one cannot trust entirely in these values as absolute quantum efficiencies.

After exposing the photocathodes to air for 1 hour, the quantum efficiency degradation values are inconclusive: one can see a slight decrease in the first values but after analysing the error bars, we can see that the supposed degradation is just fluctuations on the values. To see a more noticeable quantum efficiency degradation, a bigger exposure to air (1h/5h/10h/24h) would be necessary. [7]

The virtual instrument designed to control the setup and acquire data works almost perfectly. Nevertheless, the software is still in a early stage and there is room for many improvements.

## 7 Outlook and next steps

Overall, the setup executed the first intended tasks: to control all the moving parts, to irradiate the samples and to measure their quantum efficiencies. With this, we can already characterise photocathodes. Later, it is important to have a perfect alignment on the beam to be able to get absolute quantum efficiency values.

After this, it is necessary to assemble the irradiation chamber to be able to reproduce ageing effects. We are also expecting to be able to apply some protective layers to the photocathodes to see how the photocathodes' quantum efficiencies are affected by this. Then, with the irradiation chamber, we will also be able to see how each protective layer reacts to radiation and/or ion bombardment.

## 8 Acknowledgements

I would like to thank and express my deep appreciation to all the members of the Gas Detectors Development group (CERN) for all the material, help and suggestions that contributed to the realisation of this project. The constant good environment in the laboratory and the willingness to help was definitely an important key to the good outcome of the project.

A special thank to both my supervisors, Dr. Brunbauer and Dr. Ropelewski who were always available to answer any question or doubt regarding the project, and help in any subject concerning life in a foreign country.

I also want to thank Miranda van Stenis for the help with manufacturing setup components.

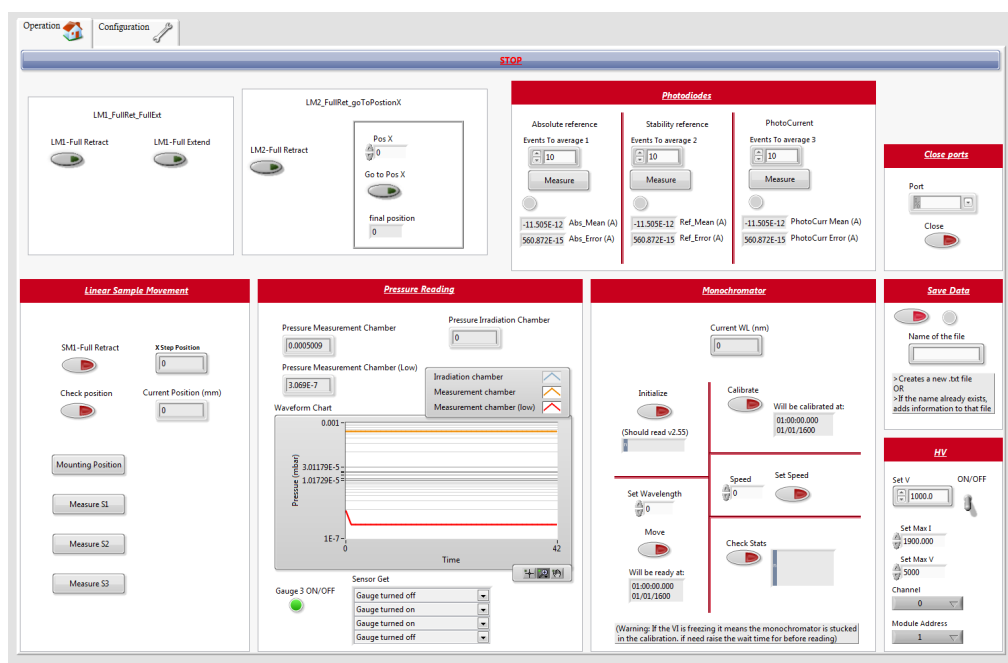
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# Appendices

## A Virtual instrument latest preview



## B Photo timeline

