HRPPD aging evaluation [at Jefferson Lab]

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Executive summary

The document provides a description of EIC HRPPD aging studies program to be conducted at Jefferson Lab or elsewhere by early 2025. The procedure is based to a large extent on a technique developed by UT Arlington group and presented at LAPPD / HRPPD Workshops in 2022 [1] and 2024 [2]. Instead of flooding the whole photosensor surface with abundant light, we are going to investigate a possible gain and photocathode efficiency drop for small active surface areas illuminating HRPPD by a focused pulsed laser light of appropriate intensity. This technique allows one to perform several sequential studies under different high voltage configurations with the same HRPPD, and also to minimize the apparent damage to its photocathode, which will be mostly localized in the illuminated spots [2].

The procedure we are presenting here is however a substantial departure from [1], because (1) its primary goal is *to prove that EIC HRPPDs will work under conditions typical for their installation place in ePIC* rather than to conduct a comprehensive study, (2) extracted anode charge used as a measure of aging in such comprehensive studies to date (see e.g. [3]) is a rather indirect proxy of the actual parameter which drives the photocathode aging, namely the integrated ion backflow mostly produced by MCP#1 in the HRPPD stackup, (3) in a setup with a readily available pulsed laser, a Photon Detection Efficiency (PDE) looks like a more natural parameter to evaluate the photocathode degradation than a Quantum Efficiency (QE).

Photocathode degradation results will therefore be presented as a *PDE drop in a single photon mode* as a function of *integrated photon flux*.

Gain degradation is of a little concern at the expected photon fluence, however the evaluation for this performance parameter will be provided as well.

Basic considerations

Essentially one has to measure some quantity Υ which characterizes aging as a function of some other accumulated quantity $\mathcal{X}$ which characterizes the damaging factor (caused by incident light), normalized to an affected surface area S: $\Upsilon_n = \Upsilon(\mathcal{X})/S$. We argue that all three ingredients are not really uniquely defined, especially in case of an accelerated pixel aging, which we chose to conduct the study, in particular if a primary concern is a photocathode efficiency degradation due to ion bombardment rather than an overall HRPPD gain drop due to the MCP secondary emission layer wearing out.

A characteristic Υ to be measured

Historically (see [1], [3], and the most recent [4]), a Quantum Efficiency (QE) degradation was used as a measure of the photocathode damage.

We argue that in a pulsed laser setup it is more natural to measure a Photon Detection Efficiency (PDE) drop directly. First, this requires almost no changes between a setup used for aging (a laser source, a "regular" HV power supply and waveform digitizer electronics) and a photocathode current measurement setup used for a QE measurement (typically a more powerful light source, and a picoammeter to both provide the HV and measure the photocathode current). Second, a quantity of interest for a Cherenkov light imaging detector (like ePIC pfRICH) based on a single photon detection is a PDE rather than a QE anyway, even that a collection efficiency CE in a formula PDE = CE*QE is supposed to be a constant.

We propose to measure a PDE degradation in a single photon mode as a measure of aging.

A quantity $\mathcal{X}$ which defines photocathode aging

Historically (see the same references), an anode extracted charge in C/cm^2 was used as an "independent" variable which characterizes the damaging factor. This one is indeed adequate in a "normal rate" aging scenario and if both MCPs biased in a pre-defined (say a symmetric) way.

However, it is a well-known fact (which we are going to prove experimentally) that ions produced in MCP#2 have little to none effect on the photocathode aging. After all, this is why a chevron MCP configuration is used in all modern MCP-PMTs. It is also clear that an asymmetric biasing scheme *in the experiment* to achieve a desired overall gain (running MCP#1 at a voltage substantially lower than MCP#2) reduces aging and has seemingly only a minor effect on other performance characteristics like timing resolution [2]. Therefore, essentially everything what happens past the transfer gap between the two MCPs, is pretty much irrelevant to characterize the photocathode aging. It is only the extracted charge at the exit of MCP#1 which matters. Besides this, it may be beneficial to drastically reduce MCP#2 bias voltage *during aging procedure itself* in order to avoid saturation, in which case extracted anode charge becomes a completely irrelevant quantity.

Since measuring MCP#1 bottom electrode current in a pixel based aging procedure may be challenging, a natural question occurs: why use a secondary quantity what the extracted charge is, in the first place? Experimental requirements at ePIC are formulated in terms of the integrated incoming charged particle flux anyway. The latter can be translated into a detected integrated photon flux (aka fluence) seen by the photocathode.

We propose to use a laser photon fluence (in γ/cm^2) as a direct measure of a damaging factor.

Light source

A pulsed laser with intensity regulated by changing a trigger pulse frequency would be desired for single photon measurements anyway. As long as a PDE rather than a QE is a primary quantity of interest, and a laser intensity per bunch is sufficient to generate a required photon flux over a small area to be illuminated, there is likely no reason to switch to a CW light source for a photon fluence accumulation either.

We will be using a PiLas PIL040 405 nm picosecond laser as a single light source in these studies.

Single vs multi-photon mode

A single-photon mode will be used for PED and gain measurements.

However, there seems to be no real reason to run a pulsed laser in a single photon mode *to age the photocathode* (like it was done in [1]). Vice versa, it may be beneficial to run the laser in a mode with ~1000 photons per bunch, lower down the MCP#2 gain to ~1 in order to avoid its saturation, and still be able to observe well-defined pulses within a dynamic range of the available DRS4 waveform digitizer. As long as an overall HRPPD gain (manifested by the measured amplitude of these pulses) for a chosen accelerated aging set of conditions does not drop with increase of a pulse frequency, we are not in a saturation mode.

We will be using a multi-photon mode to accumulate photon fluence.

Laser pulse intensity can be regulated either via a so-called laser tune or using a set of neutral density filters.

It is worth mentioning that a necessity to prove that MCP#1 is not in a saturation mode under a given choice of its bias voltage, as well as laser repetition rate and bunch intensity, and other factors is the only reason to power up MCP#2 during aging process at all. Once this proof is obtained, one in principle can run the setup with a top electrode of MCP#2 as a ground one.

Accelerated vs "normal" aging

In terms of the photocathode degradation, as long as MCP#1 is not in a saturation mode during a photon flux accumulation process (what aging procedure per se is), there should *likely* be no substantial difference between the damage after an accelerated and a "normal rate" aging procedures if the integrated photon flux (fluence) is the same in both cases. Photon flux should just be chosen as high as possible (until gain saturation starts) to conduct the measurements in the shortest period of time.

An affected surface area estimate

One disadvantage of a pixel-based aging is that quantifying an illuminated surface area S requires a bit of a consideration, especially if the laser beam is focused onto an area substantially smaller than the actual ion bombardment area on the photocathode. It is more or less clear that it is not the light spot size which should be placed in the denominator of a $\Upsilon_n = \Upsilon(X)/S$ formula, but rather a properly normalized size of the photocathode area which exhibits an apparent damage as measured after a 2D PDE scan. However, it is expected that for a beam size of 1-3 mm diameter and a photocathode voltage of 100-200 V the ion bombardment area will be well localized [2]. In this case, a PDE drop in the center of the expected bell shape profile can be taken as a measure of damage for the accumulated photon fluence, perhaps after some re-normalization to be determined experimentally. We will make an effort to establish running conditions when this bell shape damage profile seen in [2] has a flat top, at a cost of more photocathode area becoming unusable for any future applications of HRPPD under study.

Expected photon fluence in ePIC experiment

The main source of photons hitting the HRPPD photocathode will be Cherenkov ones produced in HRPPD window by charged particles with a momentum above threshold.

A gist of the Monte-Carlo simulations which summarize the actual *detected* photon fluence expected at the pfRICH location in ePIC, is presented in Figure 1, for min bias and proton beam gas background events combined, assuming a running efficiency equivalent to 26 weeks per year at a design luminosity of 10^{34} cm^{-2} s^{-1}. We come to a conclusion that HRPPDs located close to the beam pipe will experience a fluence of up to ~10^{13} *detected* Cherenkov photons per cm^2 over ten years or ePIC running.

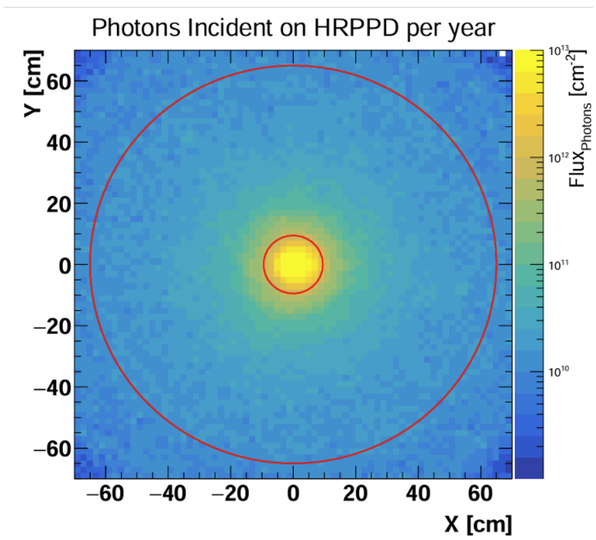

Figure 1 A detected Cherenkov photon flux incident on HRPPD photocathodes at pfRICH location in ePIC over a year of running.

This estimate is partly based on a pfRICH standalone Monte-Carlo, which takes into account a typical expected HRPPD QE(λ) curve, and shows that an energetic charged particle hitting the sapphire window at a normal incidence will produce ~100 detected photoelectrons. Particles traversing the window at a substantial angle will of course produce more. We ignore this complication in the ballpark number estimates, especially since we are mostly concerned about HRPPDs around the beam pipe, where both the primary beam gas background events and the min bias ones will produce secondaries at pretty much a normal incident angle to the window.

A safety factor of ~100 should probably be applied to the above estimates, until results of a Monte-Carlo with e/m and hadronic showers in the detector material are available. A ballpark value of the required photon fluence to accumulate in these aging studies is therefore ~10^{15} per cm^2 for the four pfRICH HRPPDs installed around the beam pipe.

It should be noted that the majority of pfRICH HRPPDs, installed further away from the beam pipe, will experience 1-2 orders of magnitude smaller charged particle fluence.

Experimental setup

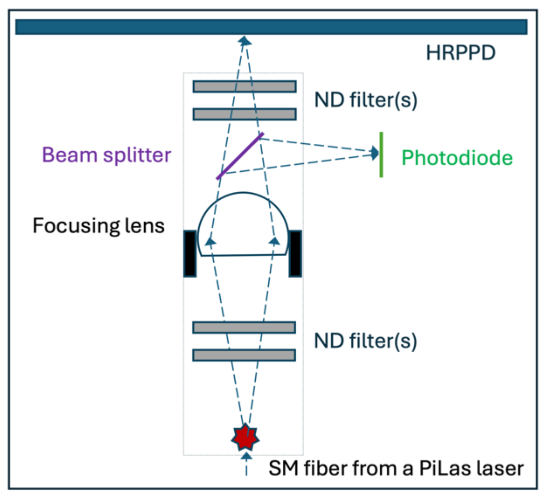

Figure 2 Optical head setup.

A sketch of an optical head mounted on an XYZ motion control system (a set of three Velmex linear stages) next to an HRPPD window is shown in Figure 2. A pulsed PiLas PIL-040-FC picosecond laser light with a wavelength of 405 nm will be coupled to the optical head via a single mode fiber with a mode field diameter ~3 µm, passed through an appropriate beam splitter, and focused on the HRPPD photocathode surface into a spot of about ~1-3 mm diameter for a photon flux accumulation and perhaps ~100-300 µm for PDE and gain surface scans on a sufficiently fine 2D grid around the illuminated spot. Position of the spot on the HRPPD surface will be regulated by the XY-stages. Spot size on the HRPPD photocathode will be regulated by the Z-stage. During illumination, the spot will be centered at the location of a particular 3.25 mm x 3.25 mm pixel on the HRPPD anode. During PDE scans, the scan area will be limited by a 5 x 5 set of pixels surrounding the illuminated one, unless the apparent photocathode damage extends further away. A fraction of light reflected on the beam splitter will be used for the incoming flux monitoring by a calibrated silicon photodiode. Neutral density filter(s) will be installed either in front of the beam splitter or between the beam splitter and the HRPPD window or in both locations, to be defined later.

Choice of “nominal” HRPPD high voltage settings

These are the settings which is our best conservative guess of how the pfRICH HRPPDs will be operated in ePIC, and for which the expected aging should be evaluated.

A photocathode voltage setting to perform the baseline part of these studies will be ~100 V, which may or may not be a representative number in case of operation in a B-field. Measurements can be repeated at a different photocathode voltage setting depending on the outcome of the upcoming B-field studies at BNL. Alternatively, a separate set of measurements at 200-300 V can be planned from the start.

We believe that HRPPDs in ePIC will *not* be run at a gain any higher than 10^6 (SPE charge ~160 fC). This looks like a reasonable maximum one can consider for use with a low noise EICROC ASIC (min threshold of 2-4 fC and ~1 pC full dynamic range), given a necessity to minimize aging but also to fit larger multi-photon signals (order of a dozen of photoelectrons per HRPPD pad) into the same dynamic range.

As a conservative emulation of running conditions in the experiment we will be using a symmetric MCP#1 and MCP#2 biasing scheme to start with (same voltage setting for both MCPs), unless first measurements show that a photocathode aging is more intense than expected. In the latter case MCP#2 bias voltage will be set to its safe operating maximum, and MCP#1 bias voltage will be fixed at a minimum required to achieve a desired overall gain.

As will be shown later, transfer gap voltage (between MCP#1 and MCP#2) and extraction voltage (between MCP#2 and anode) are not that much critical for the aging studies, and will be set to just some reasonable value like 200 V.

Input from HGCROC3 ASIC backplane evaluation and B-field studies

The HRPPD HGCRO3 backplane studies and B-field studies at BNL conducted independently, are supposed to provide a confirmation that a gain of ~10^6 is a comfortable estimate of how HRPPDs should be run for ePIC pfRICH to achieve the required level of performance in terms of e.g. a single photon timing resolution when using a TOA/ADC ASIC architecture, in a ~1.7 T magnetic field inclined up to 13^0 to the window normal (pfRICH case).

Relative contributions of MCP#1 and MCP#2 to the ion backflow

It is expected that ions produced in MCP#2 have rather limited effect on aging, because in a chevron MCP stack configuration they largely get absorbed in the micro channels of MCP#1.

A signature of photocathode bombardment by ions is so-called afterpulsing events, when the “main” anode pulse, produced by a photoelectron after its parent photon conversion in the photocathode, is accompanied by one or more pulses with a delay of up to few hundred ns. This delay mostly depends on a charge/mass ratio of a particular ion, a location where it was either desorbed from a channel wall or originated from an ionized residual gas molecule in the vacuum volume during electron avalanche development, as well as on gap values in the HRPPD stackup and respective voltages in these gaps.

To give a numerical estimate, a hydrogen ion produced at the entry of MCP#1, for a 1.1 mm gap between the photocathode and MCP#1 (EIC HRPPD stackup) and a photocathode voltage of 100 V will travel between MCP#1 and photocathode for ~16 ns, before producing a splash of secondary electrons there, and these electrons will be seen as a pulse with a delay of roughly the same ~16 ns with respect to the primary photoelectron signal.

The respective formula for this example case is $dt = g * \sqrt{(2m/(q*dV))}$, where dt is the ion travel time, g is the gap, m and q are the ion mass and charge, respectively, and dV is the photocathode voltage. A typical delay time distribution of such afterpulses is shown in Figure 3 (see slide 18 in [1]).

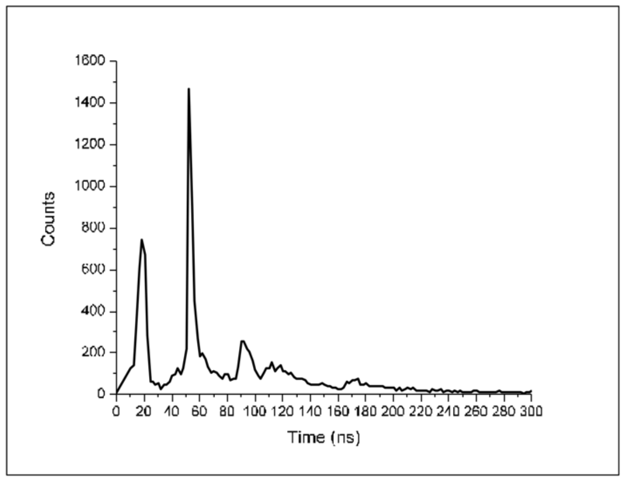

Figure 3 Afterpulses delay with respect to the primary photoelectron signal for events where only one such afterpulse was detected. Study was performed with LAPPD #64, photocathode gap 0.1", voltage 100 V.

For ions produced in MCP#2 there will be a corresponding delay caused by a time needed to travel through the 1.2 mm transfer gap between MCP#2 and MCP#1. Since this delay will (1) depend on the transfer gap voltage, (2) does not affect timing of the ions produced in MCP#1, one should be able to disentangle contributions of MCP#1 and MCP#2 in a picture like Figure 3 by simply varying the transfer gap voltage, and checking which part of the picture moves and which remains intact. Once this is done *for the expected HRPPD operating conditions in ePIC*, it is sufficient to only evaluate aging caused by ions produced in MCP#1, and rescale the estimates accordingly in case there is any measurable contribution from MCP#2.

Choice of HRPPD high voltage settings for photon flux accumulation

Once it is proven that evaluating aging caused by ions produced in MCP#1 is sufficient to perform the required study of HRPPD photocathode degradation, the strategy (which was seemingly first proposed by the UT Arlington group, even that it was not presented in [1]), is to bring MCP#1 close to a saturation mode, in a controlled way, without actually saturating the HRPPD as a whole.

In the following, we take data from Incom's own HRPPD #23 test report [5] to provide numerical estimates. A curve in Figure 5 of this report (HRPPD gain as a function of *observed* pulse rate) was obtained by illuminating a ~1 mm^2 spot on the HRPPD photocathode by a 405 nm PiLas laser with a pulse intensity close to a single photon mode. As seen from the figure, HRPPD was able to maintain a gain above 10^7 up to a repetition rate about 10 kHz, at which point MCP#2 started saturating.

Assuming for simplicity that MCP#1 and MCP#2 contributed equally to the amplification process, namely their individual gains were ~$3*10^3$ in this configuration **A**, we argue that for aging studies one can establish a stable HRPPD running configuration **B** where (1) MCP#1 bias voltage is kept the same as before, (2) laser pulse population is increased to ~$3*10^3$ photons, (3) an effective gain of MCP#2 is decreased all the way down to ~1 by either decreasing its bias voltage or by running a transfer gap in a negative bias mode. This configuration will likely provide anode signals with the same amplitude as before, since absence of MCP#2 gain will be compensated by the increased laser pulse population.

Since MCP#2 was not saturated under the original running conditions of configuration **A** (single photon mode, symmetric biasing scheme), MCP#1 will likely not be saturated in a configuration **B**, up to the same ~10 kHz laser repetition rate. One can verify this directly by checking the pulse height of the produced signals as a function of laser repetition rate.

10 kHz rate with a pulse population of ~3000 over a ~1 mm^2 spot translates into a photon flux of ~$3*10^9/cm^2s^{-1}$, which means that a required fluence of ~$10^{15}/cm^2$ can be achieved in ~$3*10^5$ s, which is about 3.5 days. A complete procedure will of course take more time because of the required periodic surface area scans, see the following section.

It should be noted that the laser spot size can be increased up to ~3 mm (and repetition rate increased accordingly by a factor of ~10) without saturating MCP#1. This obviously does not increase the *photon flux* per cm^2, but allows one to increase a *signal amplitude* in the illuminated pixel by a factor of ~10 if needed, since electron cloud at the anode will still be mostly contained in this pad.

HRPPD PDE and gain degradation evaluation

High photon flux illumination will be stopped periodically, and HRPPD returned back to its nominal HV setting (symmetric MCP bias matching a nominal gain of 10^6 before the irradiation started). Laser beam will be focused to a few hundred μm diameter spot. Laser pulse intensity will be brought down to a single photon mode. A photocathode area of 3x3, 5x5 or more pads around the illuminated one will be scanned with a step to be defined later.

Counting rate map in this single photon mode will be compared against the map measured before the irradiation started and serve as a measure of PDE degradation.

Charge accumulated by a group of 3x3 neighboring pads will be taken as a measure of HRPPD gain, and compared against the gain map measured before the irradiation started. It should be understood that this estimate only characterizes a possible wear of MCP#1. A wear estimate of MCP#2 in the experiment matching a fluence of ~10^{15} photons per cm^2, would require ~$3*10^3$ more time to obtain. However, as mentioned earlier, gain deterioration is not really expected at this level of illumination in ePIC, it is of less concern than a PDE degradation anyway, and 64 out of 68 HRPPD tiles in pfRICH will see charge particle fluence 1-2 orders of magnitude smaller than the four tiles around the beam pipe.

References

[1] V. Chirayath, A. Brandt "Pixel-based accelerated aging of Large Are Picosecond Photodetectors (LAPPDs)" , 2nd LAPPD Workshop, October 2022.

[2] V. Chirayath "Recent results from the pixel-based accelerated aging of Large Area Picosecond Photodetectors (LAPPDs)" , 4th LAPPD / HRPPD Workshop, May 2024.

[3] A. Lehmann et al. "Systematic approach to measure the performance of microchannel-plate photomultipliers" , Nucl. Instrum. Meth. A 1065 (2024) 169536.

[4] eRD110 FY24 report (slide 14) , EIC Project R&D Detector Advisory Committee meeting, August 2024.

[5] Measurement & Test report for Incom's HRPPD #23.