

Department of Physics and Measurement Technology

Master's Thesis

**Investigation of Ageing effects and Image stability
in Hybrid Photon Pixel detectors at the LHCb
experiment CERN**

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LITH-IFM-A-EX--10/2227--SE



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Sammanfattning Abstract The world's largest particle accelerator, Large Hadron Collider, located at CERN outside Geneva performed its first proton-proton collisions in November 2009. One of the four main experiments is LHCb, studying rare decays of hadrons containing the beauty quark. An essential part of the particle identification in LHCb is made by the two Ring Imaging Cherenkov detectors. These detectors use pixel Hybrid Photon Detectors for detection and imaging of Cherenkov rings. This paper reports on measurements carried out on the Hybrid Photon Detectors, including a discussion of the results. In particular, ageing effect and image stability are studied. A fraction of the photon detectors show a degradation in performance within these fields.		
Nyckelord Keywords Ring Imaging Cherenkov (RICH) detectors, Hybrid Photon Detectors (HPD), Ion Feedback (IFB), Glow light		

Abstract

The world's largest particle accelerator, Large Hadron Collider, located at CERN outside Geneva performed its first proton-proton collisions in November 2009. One of the four main experiments is LHCb, studying rare decays of hadrons containing the beauty quark. An essential part of the particle identification in LHCb is made by the two Ring Imaging Cherenkov detectors. These detectors use pixel Hybrid Photon Detectors for detection and imaging of Cherenkov rings. This paper reports on measurements carried out on the Hybrid Photon Detectors, including a discussion of the results. In particular, ageing effect and image stability are studied. A fraction of the photon detectors show a degradation in performance within these fields.

Sammanfattning

Världens största partikelaccelerator, LHC, belägen vid CERN utanför Genève utförde sina första proton-proton kollisioner i November 2009. Ett av de fyra huvudexperimenten är LHCb, som studerar sällsynta sönderfall av hadroner innehållande b kvarken. En viktig del av partikelidentifikationen i LHCb görs av de två RICH detektorerna. Dessa använder hybrida fotondetektorer för detektering och avbildning av Cherenkov ringar. Denna rapport handlar om mätningar utförda på dessa hybrida fotondetektorer, med en diskussion av resultaten. I synnerhet studeras åldringseffekter och bildstabilitet. En andel av fotondetektorerna visar en degradering i prestanda inom dessa områden.

Thesis Structure

Chapter 1 is a general introduction to CERN, the Large Hadron Collider, the LHCb experiment and its Ring Imaging Cherenkov detectors. Chapter 2 introduces the pixel Hybrid Photon Detector and its main components.

Chapters 3 and 4 contain the work of the author. Chapter 3 starts with an introduction to ageing effects in LHCb Hybrid Photon Detectors, investigated by people of the RICH collaboration. Measurements made by the author are presented from Section 3.4 and onwards.

Chapter 4 discusses the image stability in LHCb Hybrid Photon Detectors. Besides Section 4.2.3 this analysis has been performed by the author, on data coming from test runs with the photon detectors.

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Chapter 1

Introduction

1.1 CERN

The name CERN comes from French and is an acronym for Conseil Européen pour la Recherche Nucléaire which translates to European Council for Nuclear Research.

CERN is located at the Franco-Swiss border close to Geneva and was founded in 1954 as a scientific collaboration between 12 European countries. This has later been extended to include 20 member states, several observer states and other states involved in CERN programmes originating not only from Europe but from all over the world. United Nations Educational, Scientific and Cultural Organization (UNESCO) is also an observer and played an important role in setting up CERN.

CERN's main mission is stated in the convention established in 1954 and primarily states; "The Organization shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character (...). The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available".

CERN's a little more than 50 years long history includes a lot of major scientific and technical breakthroughs, like the creation of antimatter atoms, invention of the world wide web and the discovery of the $W^\pm$ and Z^0 bosons¹. Also several Nobel prize laureates through the years are connected to CERN.

The accelerator complex at CERN is a succession of machines able to accelerate particles to increasingly higher energies. Each machine injects the beam into the next one, which takes over to bring the beam to an even higher energy, and so on. Protons are extracted from hydrogen atoms and accelerated in smaller accelerators before ending up in the Large Hadron Collider where collisions are studied at the different LHC experiments (Fig. 1.1).

¹mediators of the weak interaction between particles

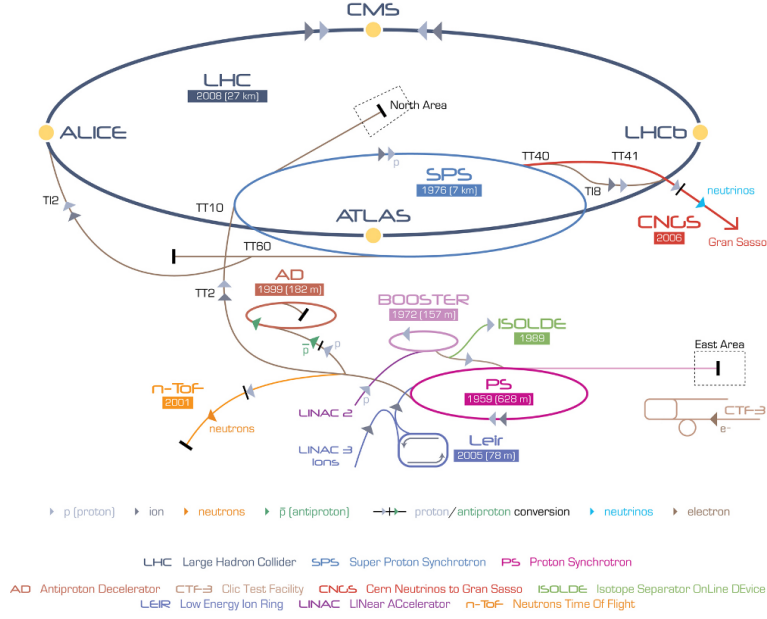


Figure 1.1. Schematic showing how particles will travel in CERN's accelerator complex. Copyright CERN PhotoLab, Christiane Lefevre.

1.2 LHC

The Large Hadron Collider (LHC) is today considered to be the flagship of CERN (Fig. 1.2). Located approximately 100 m underground, with a circumference of nearly 27 km and a total of about 9600 magnets of different types inside, the LHC is without doubt the world's largest particle accelerator and subatomic microscope [1]. The LHC is a two-ring-superconducting-hadron accelerator and collider having two counter-rotating beams of protons colliding with up to 14 TeV at a rate of 40 MHz, this corresponds to protons traveling faster than 99.99 % of the speed of light in vacuum. When LHC is operating, trillions of protons will race around the accelerator ring 11 245 times a second. LHC is also designed to accelerate and collide heavy (lead) ions with a maximum energy of 2.8 TeV per nucleon.

1.2.1 Physics

The aim of LHC is to probe a possible extension of the Standard Model of Particle Physics [1]. For this purpose two parameters of the accelerator are especially important: The center of mass collision energy, $\sqrt{s}$, which determines the energy available to produce new particles, and the luminosity, $\mathcal{L} = \frac{N_{event}}{\sigma_{event}}$, which is a measure of the particle flux and hence gives the rate of interaction in the collisions (N_{event} is the number of events per second generated in the LHC collisions and σ_{event} is the cross section for the event under study). The energy is increased by applying an electromagnetic field and hence accelerate the charged particles,

while the luminosity is increased for example by focusing the beam with powerful quadrupole magnets close to the interaction points or by increasing the number of particles in a bunch. The machine luminosity depends only on the beam parameters and can be written for a Gaussian beam distribution as [1]:

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F \quad (1.1)$$

where N_b is the number of particles per bunch, n_b the number of bunches per beam, f_{rev} the revolution frequency, γ the Lorentz factor, ϵ_n the normalized transverse beam emittance, β^* the beta function at the collision point, and F the geometric luminosity reduction factor due to the crossing angle at the interaction point (IP). The LHC design beam parameters states a maximum proton collision energy of 7 TeV and a maximum luminosity of $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Besides proton-proton collisions also heavy ion collisions of lead are foreseen as a part of the initial LHC programme and there is one experiment especially dedicated to the study of these ion collisions. Heavy ion collisions can produce a state of matter known as quark-gluon plasma (QGP) where quarks are free from each other instead of being bound via the strong force carrier, the gluon.



Figure 1.2. Photograph of the LHC accelerator taken in the tunnel. Copyright CERN PhotoLab, Maximilien Brice.

1.2.2 Design

Magnets are important components of the LHC and both superconducting and normal conducting magnets are used. The maximum beam energy that can be

reached is limited by the peak dipole magnet field² in the storage ring, which has a nominal value of 8.33 T. The magnetic length of a main dipole is 14.312 m at nominal field, hence an effective bending power of ~ 119 Tm is provided by the dipole. Besides dipole magnets which are being used for bending the beam, several other types of magnets like quadrupoles, sextupoles, kicker and septum magnets are used for beam correction, focusing, defocusing, beam dump and stabilizing the beam. To get superconducting properties of the magnets, most sectors of the accelerator operate at -271.3°C , a temperature only 2 K above absolute zero. To achieve this low temperature superfluid helium is used in a cryogenic cooling system. To accelerate the beam and keep the energy constant a superconducting radio frequency cavity system is used. The beam itself will travel in an ultra-high vacuum beam pipe with a pressure of around 10^{-8} Pa [1].

1.2.3 Experiments

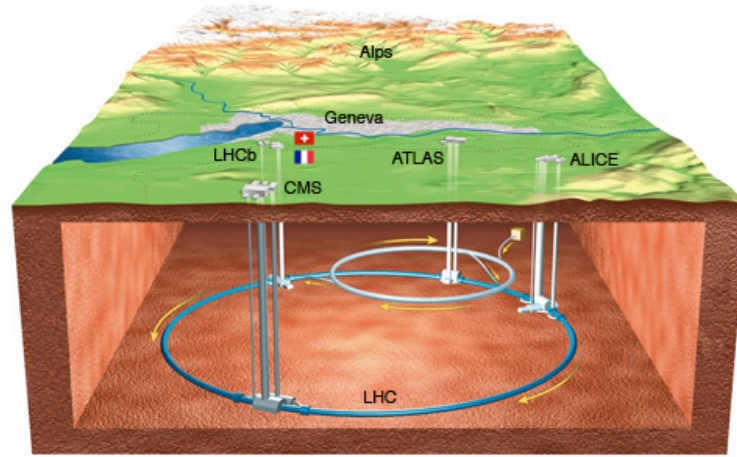


Figure 1.3. An underground schematic showing the Super Proton Synchrotron (SPS), LHC and the four main LHC experiments. Copyright CERN PhotoLab, Philippe Mouche.

There are four large-scale main experiments placed along the LHC accelerator ring: ALICE [2], ATLAS [3], CMS [4] and LHCb [5] (Fig. 1.3). In addition there are two smaller LHC experiments, the LHC Forward experiment [6] and the TOTEM experiment [7]. All the main LHC experiments aim to study the particle collisions but from different viewpoints:

²the magnetic flux density, $\mathbf{B}$, which is measured in tesla or weber per square meter, is normally referred to as the B-field or the magnetic field. This should not be confused by the magnetic field strength, $\mathbf{H}$, which is measured in ampere per meter. I will throughout the thesis use the nomenclature B-field and magnetic field

ALICE

ALICE (A Large Ion Collider Experiment) is dedicated to study collisions of heavy lead ions and from that the state of matter known as QGP, which is believed to have existed $\sim 10^{-12}$ - $\sim 10^{-6}$ s after the Big Bang³. Usually quarks appear bound to other quarks by the strong force carrier, the gluon, but in the QGP state quarks and gluons are free from each other in a hot dense 'soup'. To observe the QGP state very high temperature and high density quark matter are required, heavy ion collisions in the LHC should be a way to achieve this [2].

ATLAS

ATLAS (A Toroidal LHC ApparatuS) is one of the two general-purpose detectors at LHC and also the largest-volume collider-detector ever constructed. It makes use of the full luminosity provided by the LHC to investigate a wide range of physics, for example search for the Higgs boson, extra dimensions and dark matter [3].

CMS

CMS (Compact Muon Solenoid) is the second general-purpose detector and it has the same scientific goals as ATLAS. However it uses a different technical solution and design to achieve these goals. The key feature of the experiment is the 12 500 000 kg, 4 T superconducting solenoid magnet, making the CMS detector the heaviest of all the LHC detectors [4].

LHCb

LHCb (LHC Beauty) investigates the difference between matter and antimatter by studying rare decays of hadrons containing the beauty quark. Unlike ATLAS and CMS which are high luminosity experiments, LHCb is a low luminosity experiment aiming at a peak luminosity of $\mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ [5].

1.2.4 Data storage

When in operation the Large Hadron Collider will produce around 15 000 000 gigabytes of data each year, to store this huge amount of data CERN has in collaboration with institutes from 34 different countries implemented a distributed computing and data storage infrastructure: the LHC Computing Grid (LCG). Data from the LHC experiments will be distributed around the world enabling scientists to access and analyze it from their home institute. The project is partially funded by the European Union [9].

³compare to the Planck time unit $t_p = \sqrt{\frac{\hbar G}{c^5}} \approx 5.39 \times 10^{-44}$ s which is the time required for light to travel, in vacuum, a distance of 1 Planck length $l_p = \sqrt{\frac{\hbar G}{c^3}} \approx 1.62 \times 10^{-35}$ m. $\hbar$ is the reduced Planck constant and G the gravitational constant [8]

1.3 LHCb

1.3.1 Theory

Our current scientific understanding of the universe is that everything we know to exist was created some 14 billion years ago in an explosion of energy and spacetime known as the Big Bang. In this explosion matter was created and should, according to theory, have been matched by an equal amount of antimatter. But since matter and antimatter annihilate into energy no matter should have been able to survive. However since the universe exists and seems to be comprised dominantly of matter there must be an asymmetry between matter and antimatter [10]. The global aim of the Large Hadron Collider beauty experiment, LHCb [5], at CERN is to help us understand why our universe appears to be composed almost entirely of matter but no antimatter.

The Standard Model (SM) of particle physics includes a phenomenon known as CP violation which gives rise to an asymmetry between matter and antimatter. CP violation is a violation of the postulated CP symmetry, which is the combination of symmetry under Charge conjugation (C) and Parity (P). The amount of matter in the universe can not be explained only by the level of CP violation in the Standard Model, hence it is expected that there is another source of CP violation beyond the Standard Model. B hadrons are particles containing b (beauty) or anti- b quarks and they show the most amount of CP violation presently observed, therefore it is interesting to look at them when examining this phenomenon. The LHCb experiment will look for indirect evidence of new physics in CP violation and rare decays of B hadrons. The detector of the experiment is designed to filter out B hadrons and their decay products.

1.3.2 Design

Simulations show that B hadrons formed by the colliding proton beams in LHC stay close to the line of the beam pipe. This property affects the design of the detector. Rather than surround the collision point with layers of sub detectors in a spherical way (which is common in other LHC experiments like ATLAS and CMS) the LHCb sub detectors lie in a row behind each other (Fig. 1.4). LHCb can measure particles in the forward LHC direction which appear within an angular acceptance of 10 mrad to 250 mrad vertically and 10 mrad to 300 mrad horizontally. LHCb is not using the full luminosity of $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ provided by LHC, the experiment is aiming at a peak luminosity of $\mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. At an energy of 14 TeV the $b\bar{b}$ production cross section is $\sim 500 \mu\text{b}^4$ and 10^5 $b\bar{b}$ pairs will be produced every second. A higher production rate of B hadrons is not required for the experiment, at the same time running at lower luminosity has some advantages: Events are dominated by a single proton-proton interaction per bunch crossing and hence simpler to analyze, the occupancy in the detector remains low and radiation damage is reduced.

⁴1 b = 1 barn = 10^{-28} m^2

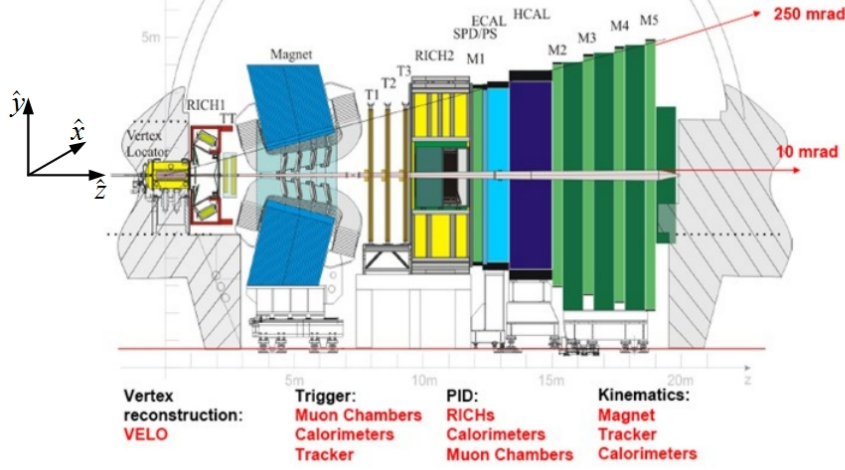


Figure 1.4. Overview of the LHCb experiment with its subdetectors. The right-handed coordinate system adopted has the z -axis along the beam, and the y -axis along the vertical [5].

Each one of the sub detectors are specialized in measuring a different characteristic of the particles produced in a proton-proton collision in LHC. All together the detector components can gather information about each generated particle including identity, trajectory, momentum and energy. The Vertex Locator (VELO) is used to pick out B hadrons among all the other particles produced in the collisions. It also performs an accurate measurement of the decay position of the hadrons and the track coordinates close to the interaction region. They are used to identify the displaced secondary vertices which are a distinctive feature of b and c -hadron decays [5]. The two Ring Imaging Cherenkov (RICH) detectors are built to determine the speed of the different particles resulting from the B hadron decays. The dipole magnet makes these particles to move in different trajectories depending on their charge and is therefore involved in determining the charge and momentum (Eq. 1.2 for the Lorentz force, where $\mathbf{E} = 0$ and $\mathbf{B}$ are the electric and magnetic fields, q the charge, $\mathbf{v}$ the particle velocity and $\mathbf{F}$ the resulting force acting on the particle).

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (1.2)$$

The trackers are used to sample the particle trajectories and hence enable these to be recorded. This is later used for reconstructing the B particle decays. The calorimeters are measuring the energy of the different particles. The muon system is, as the name suggests, detecting muons, μ , (heavy, electron-like particles) which are present in the final state of many B hadron decays⁵. Muons play a major

⁵as in $B_d^0 \rightarrow J/\psi (\mu^+ \mu^-) K_S^0$ and $B_s^0 \rightarrow J/\psi (\mu^+ \mu^-) \phi$

role in CP violation measurements and are hence very important for the LHCb experiment.

The bunch crossing frequency in the LHCb interaction point is 40 MHz but only about 10 MHz of events will be visible⁶ by the spectrometer due to the LHC bunch structure and lower luminosity at LHCb. However the rate of B hadron decays that are interesting for physics analysis is only a few Hz and to find these a two level trigger system is used. The first level trigger, called the Level-0 (L0) trigger, is a very fast system using real-time information from the detectors to select around 1 million events out of 10 millions per second. The second level trigger is called the High Level Trigger (HLT), it has more time to take a decision and is made by a system of up to 2000 servers containing CPUs with multi-core technologies, the 1 million events are here reduced to a more manageable number of 2 000 events. The data from these 2 000 events per second is transmitted to the CERN computing center and stored for further offline analysis.

1.4 Cherenkov radiation

According to Einstein's special theory of relativity light in vacuum propagates with speed c in terms of any system of inertial coordinates, regardless of the state of motion of the light source. Observations of an event from two different reference frames, S and S' , are specified by the Lorentz transformation [8]

$$\begin{aligned} t' &= \gamma \left(t - \frac{vx}{c} \right) \\ x' &= \gamma (x - vt) \\ y' &= y \\ z' &= z \end{aligned} \tag{1.3}$$

where $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$ is the Lorentz factor, (t, x, y, z) are the space-time Cartesian coordinates in S and (t', x', y', z') the corresponding in S' and v is the relative velocity along the common x -axis. The Lorentz factor implies that no frame can move faster than c relative to another frame and hence no particle can be observed to move faster than c . The speed at which light propagates in a medium is dependent on the refractive index of the medium, n , and is given by the formula $v = \frac{c}{n}$. If $n > 1$ a particle can travel faster than the speed of light inside the medium and this can be achieved for example with particle accelerators.

Cherenkov radiation is a result of a charged particle traveling faster than the phase velocity of light in a medium and can be explained by conservation of energy and momentum.

Example 1.1

Assume a particle with mass m and charge q , propagating with velocity $\vec{\beta} = \frac{\mathbf{v}}{c}$ in a medium with refractive index $n = \frac{c}{v_\Gamma} > 1$ (i.e. v_Γ is the speed of a photon in the

⁶an interaction is defined to be visible if it produces at least two charged particles with sufficient hits in the Vertex Locator and Tracker1 - Tracker3 to allow them to be reconstructible

medium). The electromagnetic (EM) field is exchanged by a virtual photon with energy E_Γ and momentum $\mathbf{p}_\Gamma$ according to Fig. 1.5. The energy and momentum of the particle are E_m and $\mathbf{p}_m$ respectively, with indices 1 and 2 referring to before and after the exchange. To simplify notation the absolute value of a vectorial entity is written in normal style, e.g. $|\vec{\beta}| = \beta$ and $|\mathbf{v}| = v$.

The following identities for a relativistic particle are used [8]:

$$E_m = \gamma mc^2 \quad (1.4)$$

$$E_m^2 = (p_m c)^2 + (mc^2)^2 \quad (1.5)$$

$$\mathbf{p}_m = \gamma m \mathbf{v} \quad (1.6)$$

$$E_m = \frac{p_m c^2}{v} \quad (1.7)$$

where γ is the Lorentz factor.

The following identities for a photon are used [8]:

$$E_\Gamma = \hbar \omega \quad (1.8)$$

$$\mathbf{p}_\Gamma = \hbar \mathbf{k} \quad (1.9)$$

where $\hbar = \frac{h}{2\pi}$ is the reduced Planck constant, ω the angular frequency and $\mathbf{k}$ the wave vector of the photon.

Conservation of energy, $E_1 = E_2 + E_\Gamma$, combined with Eq. 1.5, Eq. 1.7 and Eq. 1.8 yields

$$(p_1 c)^2 = (p_2 c)^2 + 2\hbar \omega \frac{p_2 c^2}{v_2} + (\hbar \omega)^2. \quad (1.10)$$

Conservation of linear momentum gives $\mathbf{p}_1 = \mathbf{p}_2 + \mathbf{p}_\Gamma$. Taking the scalar product of this equation with itself, multiplying with c^2 and using Eq. 1.9 yields

$$(p_1 c)^2 = (p_2 c)^2 + 2\hbar c^2 \mathbf{k} \cdot \mathbf{p}_2 + (\hbar k c)^2. \quad (1.11)$$

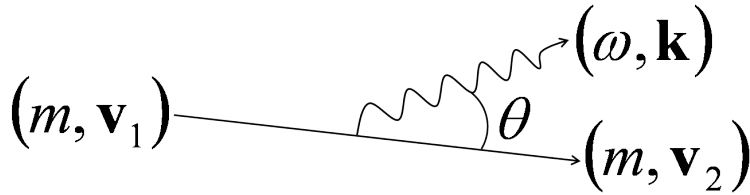


Figure 1.5. A virtual photon is exchanging the EM field of a particle.

Using the dispersion relation of a photon

$$k = \frac{\omega}{v_\Gamma} = \frac{\omega n}{c}, \quad (1.12)$$

subtracting Eq. 1.11 from Eq. 1.10 and dividing by $\hbar\omega$ gives

$$\hbar\omega (1 - n^2) + 2p_2 \left(\frac{c^2}{v_2} - cn \cos \theta \right) = 0 \quad (1.13)$$

where θ is the angle between $\mathbf{k}$ and $\mathbf{p}_2$. Assuming a refractive index relatively close to $n = 1$ and that the energy of the photon (Eq. 1.8) is small, the approximation $\hbar\omega (1 - n^2) \approx 0$ is made. Finally Eq. 1.13 then yields

$$\cos \theta = \frac{c}{nv_2} = \frac{1}{n\beta_2}. \quad (1.14)$$

Eq. 1.14 only makes sense if $\frac{1}{n\beta_2} \leq 1$ since $|\cos \theta| \leq 1$ always is true, hence $v_1 \leq v_2$. It is also true that $v_2 \leq v_1$ due to the loss in energy of the particle in the exchange. If the speed of the particle is larger than the speed of light in the medium, then the exchange photon is no longer virtual but a real Cherenkov photon.

The condition for emission of a Cherenkov photon is given by

$$\cos \Theta_C = \frac{1}{\beta \cdot \sqrt{\varepsilon_r(\lambda)}} = \frac{1}{\beta \cdot n(\lambda)} \quad (1.15)$$

(see Fig. 1.6) and the number of emitted photons by [11]

$$\frac{d^2N}{dL d\lambda} = -2\pi\alpha Z^2 \frac{\sin^2 \Theta_C}{\lambda^2}. \quad (1.16)$$

In Eq. 1.15 Θ_C is the emission angle of the Cherenkov photon ($0 \leq \Theta_C \leq \frac{\pi}{2}$), $\beta = \frac{v}{c}$ where v is the particle speed and n the refractive index. The refractive index follows the equality $n(\lambda) = \sqrt{\varepsilon_r(\lambda)\mu_r}$ where ε_r is the relative permittivity and μ_r the relative permeability [12]. μ_r describes the degree of magnetization of a material and for most materials it is very close to 1, hence the formula is simplified to $n(\lambda) = \sqrt{\varepsilon_r(\lambda)}$. The relative permittivity is often dependent on the wavelength, λ , of the light and hence the refractive index too. Equation 1.15 says that the threshold condition for Cherenkov emission to occur is given by

$$\frac{1}{\beta \cdot n(\lambda)} = \cos \Theta_C \leq 1 \Leftrightarrow \frac{c}{n(\lambda)} \leq v \quad (1.17)$$

and the maximum emission angle by

$$\cos \Theta_{max} = \frac{1}{n(\lambda)} \quad (1.18)$$

for $v = c$. A higher momentum particle will have a higher β and therefore the emission angle increases with increasing particle momentum. From Eq. 1.17 it is also clear that a higher refractive index yields a higher emission angle. Eq. 1.16 is the Frank-Tamm relation where dN is the number of emitted photons with a

wavelength in the range between λ and $\lambda + d\lambda$ over a particle path length in the medium dL . Z is the charge of the particle and $\alpha \approx \frac{1}{137}$ is the electromagnetic fine structure constant. Combining Eq. 1.15 with Eq. 1.16, we obtain

$$\frac{d^2 N}{dL d\lambda} = -2\pi\alpha Z^2 \frac{1 - \left(\frac{1}{n(\lambda)\beta}\right)^2}{\lambda^2} \quad (1.19)$$

which is the $(\beta, n(\lambda))$ spectral dependence. Integrating Eq. 1.19 we obtain the number of produced Cherenkov photons, N . Under the approximation of a constant Cherenkov angle (i.e. for constant $n(\lambda)\beta$), the integral over the length ΔL and wavelength bandwidth $\Delta\lambda$ is

$$N = 2\pi\alpha Z^2 \Delta L \sin^2 \Theta_C \left(\frac{1}{\lambda} - \frac{1}{\lambda + \Delta\lambda} \right). \quad (1.20)$$

The integration over λ has to be made from higher wavelength to lower if $\Delta\lambda > 0$, the reason is that the energy difference, ΔE , should be positive and since $E = \frac{hc}{\lambda}$ a higher λ corresponds to a lower E . Eq. 1.19 yields that the Cherenkov photon spectrum, with respect to photon energy, is flat for n constant, but for a real medium ($n(\lambda)$) decreases with λ causing the UV spectrum amplitude to rise.

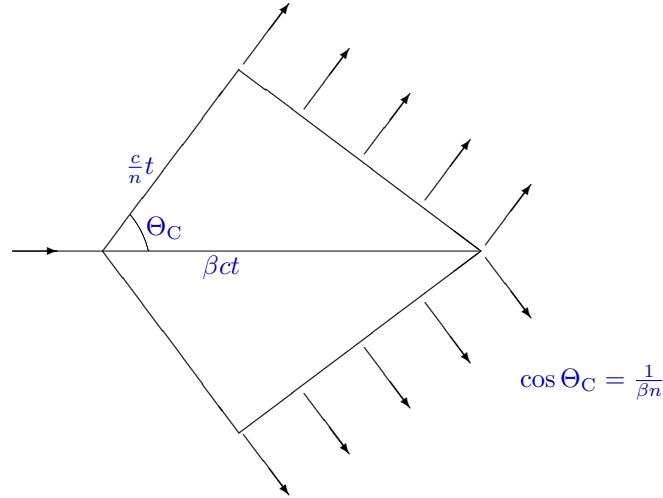


Figure 1.6. Illustration of the Cherenkov wavefront created when a particle travels faster in a medium than the speed of light in that medium.

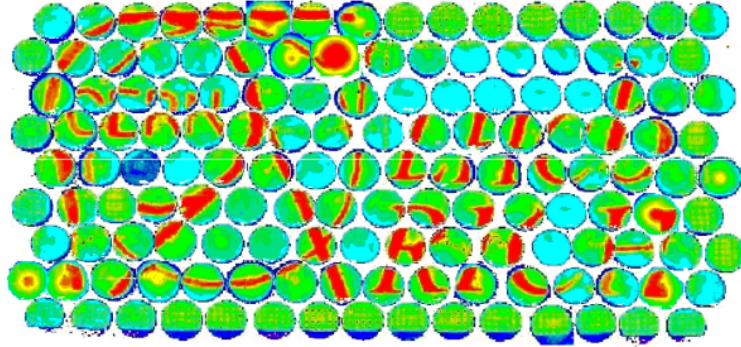


Figure 1.7. RICH, LHCb, CERN.

1.5 Ring Imaging Cherenkov detectors

1.5.1 Introduction

By knowing the refractive index, n , of the medium and measuring the Cherenkov angle, Θ_C , between the emitted light wavefront and the particle trajectory, it is possible to determine the speed of the particle (Fig. 1.6). In this way particle detectors can make use of Cherenkov radiation for measuring the speed of high-energy particles, as long as the detectors include components that are photo sensitive enough to detect the weak Cherenkov light. This is how the two Ring Imaging Cherenkov (RICH) detectors in the LHCb experiment work (Fig. 1.8).

1.5.2 Spherical mirrors

To find the Cherenkov angle, photon detectors are used to detect rings of Cherenkov light. Emitted Cherenkov wavefronts have the form of cones, inside the RICH detectors spherical mirrors focus the light cones onto the photon detector plane placed at the focal plane of the mirrors. With a spherical mirror of focal length f , the result is a ring of light with radius $r = f\Theta_C$ at the photon detector plane. The ring radius is independent of the emission point along the particle track.

An example of ray tracing in a spherical mirror is presented in Appendix Section B.1, it is intended to explain why the Cherenkov wavefronts are detected as rings at the photon detector plane.

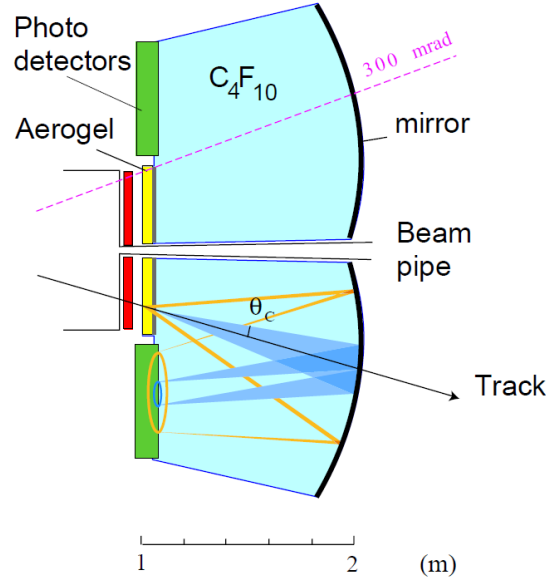


Figure 1.8. Schematic layout of a possible RICH detector. The focusing of Cherenkov light from a track passing through two radiators is illustrated [13].

1.5.3 Uncertainty estimation

Eq. 1.20 can be transformed into a detected number of photons in a RICH detector by adding the parameter ϵ ,

$$N_d = N_0 Z^2 \Delta L \sin^2 \Theta_C \quad (1.21)$$

where $N_0 = 2\pi\alpha\epsilon \left(\frac{1}{\lambda} - \frac{1}{\lambda + \Delta\lambda} \right)$ is the detector response parameter. ϵ is the energy average of detector efficiencies (quantum, transmission and mirror reflection) over the wavelength range λ to $\lambda + \Delta\lambda$, the photon detector response range.

From Eq. 1.21 we obtain the resolution $\frac{\sigma_\beta}{\beta}$ for a detector that counts Cherenkov photons (a Cherenkov counter). N_d follows a Poisson distribution, it gives the probability of finding exactly n events in a given interval in space and time when the events occur independently of each other. If the average rate is ν per the given interval, the Poisson distribution's probability density function is given by

$$f(n) = \frac{\nu^n e^{-\nu}}{n!}; n = 0, 1, 2, \dots; \nu > 0 \quad (1.22)$$

and the mean and the variance, σ^2 , are both equal to ν [14]. The standard deviation for the number of detected Cherenkov photons is $\sigma_{N_d} = \sqrt{\nu} = \sqrt{N_d}$.

Theorem 1.1 Let f be a function which is defined on the interval (a, b) and suppose the $(n + 1)^{\text{th}}$ derivative $f^{(n+1)}$ exists on (a, b) . Then for all x and x_0 in

(a, b) ,

$$R_{n,x_0}(x) = \frac{f^{(n+1)}(\xi)}{(n+1)!} (x - x_0)^{n+1} \quad (1.23)$$

with ξ strictly between x and x_0 . $R_{n,x_0}(x)$ is the remainder to the n^{th} degree Taylor polynomial approximation of $f(x)$

$$P_{n,x_0}(x) = \sum_{k=0}^n \frac{f^{(k)}(x_0)}{k!} (x - x_0)^k \quad (1.24)$$

with

$$R_{n,x_0}(x) = f(x) - P_{n,x_0}(x). \quad (1.25)$$

From theorem 1.1 (Taylor's theorem) we can obtain a formula for the propagation of uncertainty, by using the Taylor polynomial of degree 0 in Eq. 1.25,

$$N_d(\Theta_C) = N_d(\theta_0) + \frac{dN_d}{d\Theta_C}(\xi) (\Theta_C - \theta_0). \quad (1.26)$$

Assuming $\sigma_{\Theta_C} = \Theta_C - \theta_0$ is small we get the approximation

$$\sigma_{N_d} = N_d(\Theta_C) - N_d(\theta_0) \approx \frac{dN_d}{d\Theta_C}(\Theta_C) (\Theta_C - \theta_0) = 2N_0 Z^2 \Delta L \sin \Theta_C \cos \Theta_C \sigma_{\Theta_C}. \quad (1.27)$$

Combining Eq. 1.21 and Eq. 1.27 we obtain

$$\frac{\sigma_{N_d}}{N_d} = \frac{1}{\sqrt{N}} = 2 \cot \Theta_C \sigma_{\Theta_C}. \quad (1.28)$$

The same procedure on Eq. 1.15 gives

$$\frac{\sigma_\beta}{\beta} = \tan \Theta_C \sigma_{\Theta_C} \quad (1.29)$$

and combining Eq. 1.28 with Eq. 1.29 we finally obtain

$$\frac{\sigma_\beta}{\beta} = \frac{\tan^2 \Theta_C}{2\sqrt{N_d}}. \quad (1.30)$$

Eq. 1.30 describes the uncertainty of the measured particle speed $v = \beta c$ (i.e. the resolution) in a detector that counts the number of Cherenkov photons from a particle track. In a RICH detector the angle Θ_C is measured by fitting rings to the photon hits at the photon detector focal plane (Fig. 1.9) and hence the resolution is improved.

1.6 LHCb RICH detectors

For LHCb particle identification is a fundamental requirement and the identification system consists of two RICH detectors, RICH 1 and RICH 2. Together they

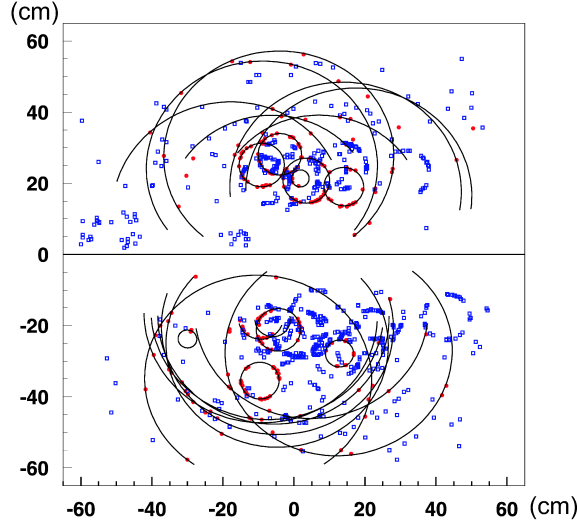


Figure 1.9. Display of a simulated LHCb event in RICH 1 [5]. The blue and red dots represent photon hits and the solid lines are fitted rings. The rings are from particle tracks passing through aerogel and C_4F_{10} radiators.

detect charged particles over the momentum range 1 - 100 GeV/ c , where RICH 1 covers the low momentum region and RICH 2 the high momentum region [13]. The main difference between RICH 1 and RICH 2 (except from RICH 2 being significantly larger in size) is that they have different kinds of radiators. A radiator is the medium that a particle travels through when it emits Cherenkov radiation, hence a radiator has a refractive index larger than the $n = 1$ of vacuum [5].

1.6.1 RICH 1

RICH 1 is located upstream of the LHCb dipole magnet between the Vertex Locator and the Trigger Tracker (Fig. 1.4) and covers the full LHCb angular acceptance from ± 25 mrad to ± 300 mrad horizontally and ± 25 mrad to ± 250 mrad vertically. It has two different radiators, Silica aerogel and the gaseous C_4F_{10} . Silica aerogel is a solid with an extremely low density and a high refractive index (around $n = 1.03$) and because of these qualities it is a perfect radiator for detecting the lowest momentum particles of a few GeV/ c . C_4F_{10} , with refractive index⁷ $n \approx 1.0014$, is used for covering a higher momentum range, from about 10 GeV/ c to 60 GeV/ c .

The schematic layout of RICH 1 (Fig. 1.10) shows that the detector has a vertical optical layout and is divided into two different parts which are symmetric to each other. The upper part is normally referred to as the U-side (Up) and the lower part as the D-side (Down), the photon detectors of RICH 1 are consequently di-

⁷refractive index for a gas depends on temperature, pressure and photon energy, (Section 1.6.3)

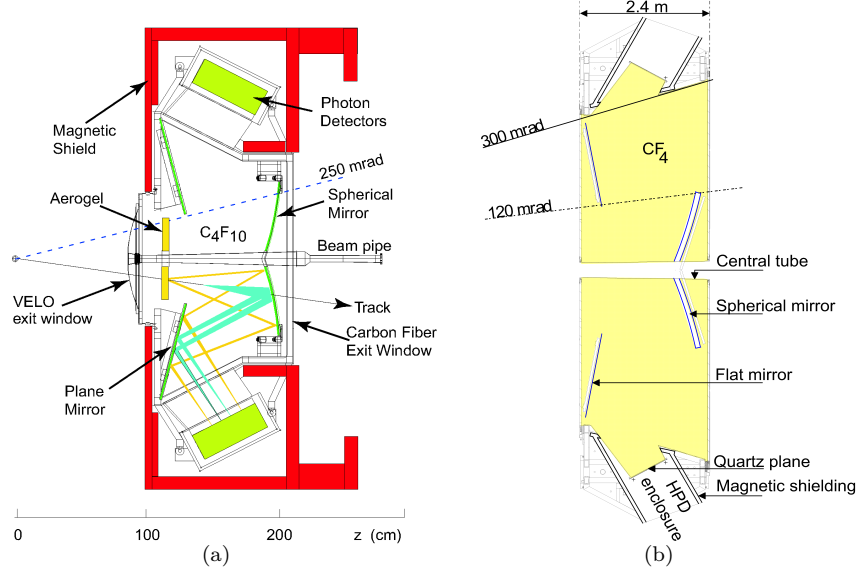


Figure 1.10. a) Schematic layout of RICH 1 seen from the side. b) Schematic layout of RICH 2 seen from above [5].

vided into two groups called the U-box and the D-box. These photon detectors are located outside of the LHCb acceptance, above and below the beamline, in a region where a magnetic iron shield can be accommodated.

Spherical mirrors

Both RICH detectors have spherical and flat mirrors for focusing of the emitted Cherenkov light and for reflecting the image out of the spectrometer acceptance (Fig. 1.10). The spherical mirrors are responsible of transforming the Cherenkov wavefront into a ring of Cherenkov light on the photon detector planes. Measuring the radius of the light ring makes it possible to calculate the Cherenkov angle and hence the speed of the corresponding particle.

The spherical mirrors inside RICH1 have a radius of curvature 2700 mm and a dimension of 830 mm $\times$ 630 mm when projected onto the x - y plane. There are two surfaces of spherical mirrors, one above the LHC beryllium beam pipe and one below. Because the spherical mirrors are located within the LHCb acceptance they are traversed by both particles and high-energy photons. Instead of glass mirrors, carbon fiber reinforced polymer (CFRP) substrate mirrors are used. This material is more lightweight and gives a lower material budget for the mirrors and the mirror support than glass mirrors do.

Flat mirrors

Additional flat mirrors reflect the Cherenkov light image from the tilted spherical mirrors onto the photon detector planes. Since the flat mirrors are located outside the LHCb acceptance, glass substrate is used. There are two planes of flat mirrors, one above and one below the beamline, which both consist of eight rectangular mirrors with dimension $380 \text{ mm} \times 347.5 \text{ mm}$.

Gas enclosure

The gas enclosure is used as a container for the C_4F_{10} gas radiator and also as a mechanically stable platform for all the optical components in RICH1. It must sustain a $\pm 300 \text{ Pa}$ pressure differential between the inside gas and the outside atmospheric environment. 8 mm thick quartz windows are used to separate the two photon detector planes from the Cherenkov gas. The enclosure is a six-sided box made of 30 mm thick aluminum, it weighs 600 kg and has a volume of 3.5 m^3 .

Magnetic shield boxes

RICH1 is located in the upstream fringe field of the LHCb dipole magnet with a field strength of about 60 mT where the photon detectors are. These photon detectors can at maximum be exposed to a magnetic field of 1 mT to operate at full efficiency, magnetic shields are required to attenuate the primary external field by a factor 20 or more [15]. Inside RICH1 there are two magnetic shield boxes each surrounding one set of photon detectors. The shield boxes are made from 50 and 100 mm thick plates of stabilized iron and have the dimension $1950 \text{ mm} \times 4000 \text{ mm} \times 1175 \text{ mm}$, they are the main part of the total weight of RICH1 being about 16 000 kg. Measurements with the shields in place and the LHCb dipole magnet at full field indicate that the maximum magnetic field strength at the photon detector plane is 2.4 mT. Additionally each photon detector is equipped with a high-permeability cylindrical shield that further attenuates the magnetic field strength to values below 1 mT.

1.6.2 RICH 2

The RICH2 detector is located downstream of the LHCb magnet between the last tracking station and the first muon station (Fig. 1.4), it has a limited angular acceptance of $\pm 15 \text{ mrad}$ to $\pm 120 \text{ mrad}$ horizontally and $\pm 15 \text{ mrad}$ to $\pm 100 \text{ mrad}$ vertically but covers the region where high momentum particles are produced. It contains only one radiator, the gaseous CF_4 with a refractive index⁷ of $n \approx 1.0005$. RICH2 identifies particles with a momentum between $15 \text{ GeV}/c$ to more than $100 \text{ GeV}/c$.

Unlike RICH1 having a vertical optical layout, RICH2 has a horizontal layout and is divided in the A-side to the left and the C-side to the right seen from the

⁷refractive index for a gas depends on temperature, pressure and photon energy, (Section 1.6.3)

incoming particles created in the collisions (Fig. 1.10). Both sides have their own set of photon detectors situated outside the full LHCb acceptance.

Spherical and flat mirrors

RICH 2 has two spherical mirror surfaces and two planes of flat mirrors, one on each side of the beamline. The spherical mirrors have a radius of curvature 8600 mm and are composed of hexagonal mirror elements with a circumscribed diameter of 510 mm, there are 26 mirrors in each plane. The flat mirror surfaces each consist of 20 rectangular mirror segments measuring $410 \times 380 \text{ mm}^2$.

The mirror support system in RICH 2 is crucial for the construction of an almost perfect reflective surface. The alignment of the mirrors must be better than 1 mrad to have a negligible impact on the reconstruction of Cherenkov rings. The stability of the support system has been tested in the laboratory for more than a year. The full system is now stable within $100 \mu\text{rad}$, fluctuations are mainly due to temperature variations.

Gas enclosure

The gas enclosure in RICH 2 has a volume of about 95 m^3 including entrance and exit windows, it is hence much larger than the gas enclosure of RICH 1. The hydrostatic pressure exerted by the Cherenkov gas CF_4 is controlled at the top of the detector to be within -100 to 200 Pa . The two photon detector planes are separated from the Cherenkov gas by 6 mm thick quartz windows.

Magnetic shield boxes

RICH 2 is positioned almost halfway between the iron yoke of the LHCb dipole magnet and the ferromagnetic structure of the hadron calorimeter, consequently the magnetic field where the photon detectors are located can exceed 15 mT and is rapidly varying in all directions. Two magnetic shield boxes are needed to attenuate the magnetic stray field by a factor of 15 or more, at the same time they should provide a mechanically stable and light-tight environment for the photon detectors. The shield boxes inside RICH 2 are made from 60 mm thick plates of stabilized iron and they have been measured to reduce the magnetic field strength to a value ranging from 0.2 to 0.6 mT at the photon detector planes. The overall weight of the magnetic shielding structure is about 12 000 kg whereas the total weight of the detector is about 30 000 kg. Like in RICH 1, all photon detectors are equipped with individual high-permeability magnetic shields to further attenuate the magnetic field strength.

1.6.3 Radiators

The radiators inside the RICH detectors are Silica aerogel, C_4F_{10} (RICH 1) and CF_4 (RICH 2) [5].

Silica aerogel is a colloidal form of quartz, solid but with an extremely low density, which is ideal to cover the difficult refractive index range between gas and

liquid. Its refractive index is tunable in the range 1.01 - 1.10, hence it is used for identification of low-momentum particles with a momentum of a few GeV/c . In RICH 1 the aerogel has refractive index $n = 1.03$ at $\lambda = 400 \text{ nm}$. Today there exist high-quality, clear samples of aerogel making it possible to use it in the RICH 1 detector, however there is still a photon loss which is mainly due to Rayleigh scattering.

C_4F_{10} and CF_4 are fluorocarbon gases that were chosen partly because their refractive indices are well matched to the momentum spectrum of particles from B decays at LHCb, but also because they have a low chromatic dispersion. The refractive indices depend on temperature, pressure and the light wavelength (Fig. 1.11), at 0°C , 101.325 kPa (standard atmospheric pressure) and 400 nm wavelength they are $n = 1.0014$ for C_4F_{10} and $n = 1.0005$ for CF_4 . In the RICH detectors the gas radiators are at ambient temperature and slightly above atmospheric pressure when the detectors are operating. Temperature and pressure are recorded and allow to correct for variations in refractive indices. There is a small contamination of air inside the detectors but this does not significantly affect the functionality. This is because the photon detectors have been chosen to detect light of wavelengths which air is transparent to. However O_2 and H_2O contaminations are kept at low level because of the possible radiation-induced formation of HF gas. CO_2 is used as a pressure-balancing gas and is kept constant at 1 % level.

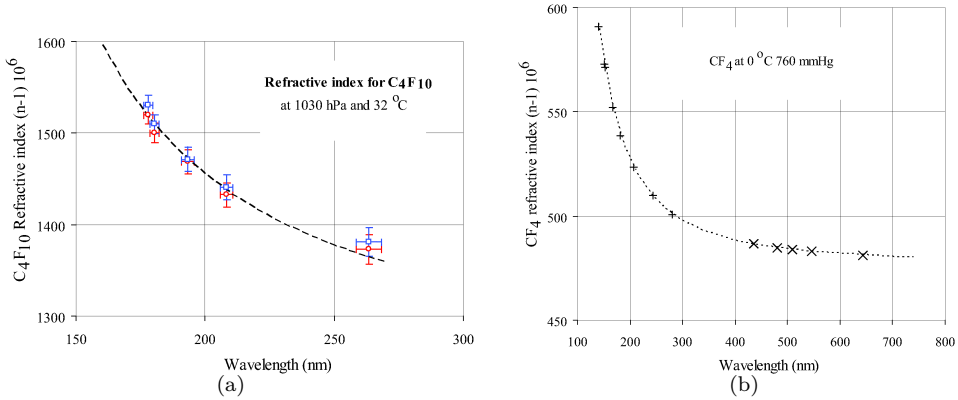


Figure 1.11. a) Refractive index of C_4F_{10} against wavelength [16]. b) Refractive index of CF_4 against wavelength [17, 18].

Chapter 2

Hybrid photon detectors

2.1 Overview

Photon detectors are devices able to convert light into detectable electronic signals. The LHCb Hybrid Photon Detectors (HPD) are vacuum tubes used to detect and measure the spatial position of Cherenkov photons in the wavelength range 200 - 600 nm emitted by particles traveling inside the RICH detectors. When a photon hits the photocathode of an HPD in operation, a photoelectron is emitted and accelerated onto a reverse-biased silicon detector. The acceleration is made by an applied electric potential inside the HPD body, typically of the order of 20 kV. When the photoelectron hits the silicon anode the energy is absorbed and thus produces electron-hole pairs, which in turn generates an electronic signal in the readout electronics. The efficiency of detecting single photons is very high for the HPD [19].



Figure 2.1. A pixel HPD used in the RICH detectors of LHCb [5].

The basic concept of HPDs has been known since 1957 but in recent years

it has been possible to start taking advantage of the improved performance of silicon diodes. Developments have been motivated by better single-photon counting, improved dynamic range, robustness in magnetic fields, and position-sensitive photon detection. Three main lines have evolved: Hybrid PhotoMultiplier Tubes (HPMTs) for photon counting and for gamma spectroscopy with scintillation detectors; Multi-Anode Photon detector (MAP) tubes equipped with several silicon pad anodes for position-sensitive photon detection; Imaging Silicon Pixel Array (ISPA) tubes, with finely segmented silicon pixel anodes for opto-electronic cameras [20].

2.2 LHCb HPDs

The hybrid photon detectors (Fig. 2.1), used in the RICH detectors in LHCb, have been developed together with the Dutch company Delft Electronic Products¹ (DEP) and are built upon the ISPA HPD type with silicon pixel anodes, hence they are called Pixel HPDs [19]. The specific requirements for the RICH detectors are a large area coverage ($\sim 3.5 \text{ m}^2$) with high active-to-total area ratio after close-packing (64 %), high granularity ($2.5 \times 2.5 \text{ mm}^2$ at the photocathode) and high speed (25 ns timing resolution) [5]. A total of 484 tubes (196 for RICH 1 and 288 for RICH 2) are used in the two RICHes. RICH 1 has 2×7 columns of HPDs with 14 HPDs per column, where the factor 2 corresponds to the U - and D-boxes (Section 1.6.1). RICH 2 has 2×9 columns with 16 HPDs per column and is divided into the A - and C-side boxes (Section 1.6.2 and Fig. 2.2).

The pixel HPD tube (Fig. 2.3) has a cylindrical form with an overall diameter of 83 mm. The entrance window is fabricated from quartz and forms a spherical surface, with 7 mm thickness and 55 mm inner radius of curvature. Besides an opening for the entrance window, each tube is completely surrounded by an 1 mm thick high-permeability metal cylinder of 140 mm length and 86 mm outer diameter which works as a magnetic shield, protecting against B-fields up to 5 mT. A tube is photosensitive over a 75 mm diameter and inside both RICH detectors the tubes are packed in a hexagonal close packing (0.907 coverage) with a tube-to-tube pitch of 89.5 mm. This gives an effective area of $\epsilon_A = 0.907 \times (75/89.5)^2 \approx 0.64$. The power supply for the HPDs is a low-ripple supply with a 300 M Ω voltage divider, which provides high voltages to the tubes. Each column of HPDs has its own HV supply which means that if something is wrong on one column the other columns can still operate.

Inside, the HPD is biased with a nominal applied voltage of -20 kV from the photocathode at the inside of the entrance window to the silicon sensor anode on the other side of the tube. The first and second electrodes in the tube, are at -19.7 kV and -16.4 kV respectively. When a photon hits the photocathode it releases a photoelectron which accelerates in the electric field towards the anode, where it strikes a segmented silicon pixel sensor releasing ~ 5000 electron-hole pairs (Fig. 2.4). The silicon pixel anode is bump bonded to a binary readout chip which registers a signal. The image coming in to the tube (that is the photons)

¹now Photonis-Netherlands B.V.

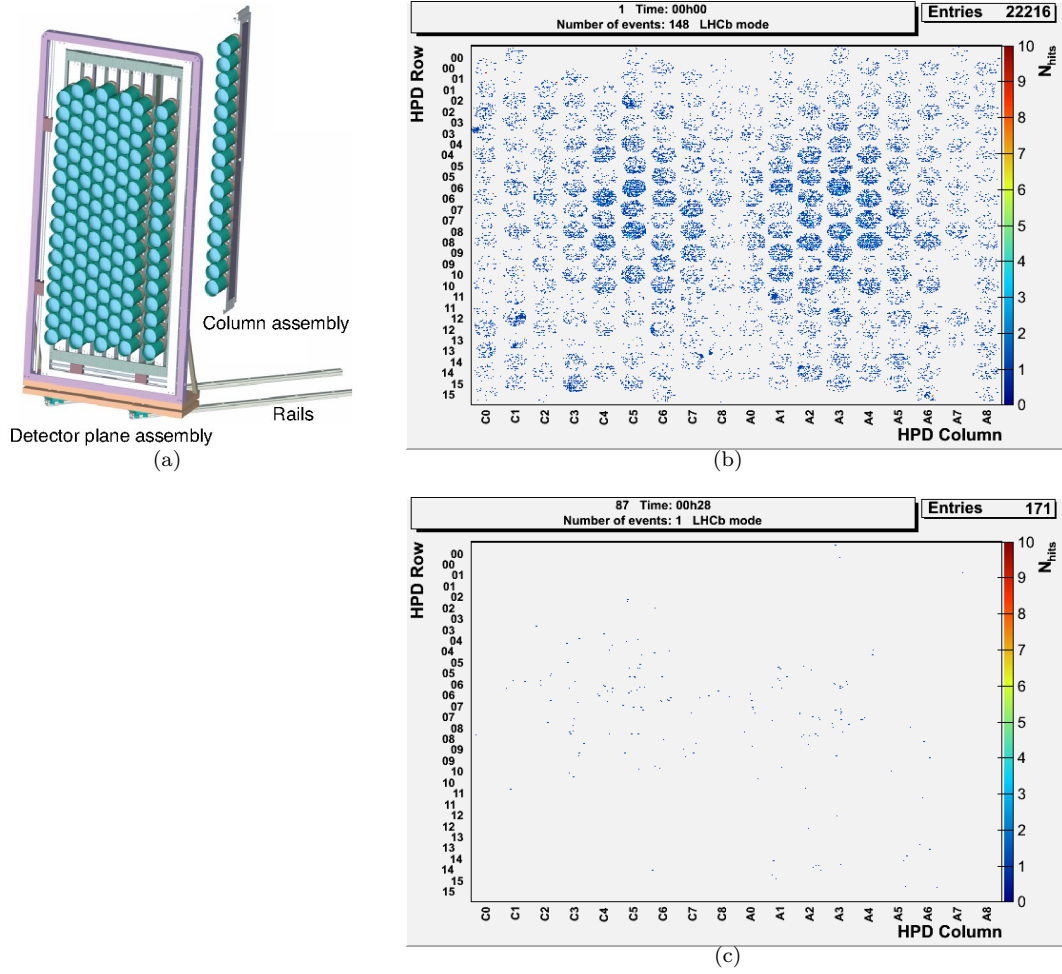


Figure 2.2. a) The RICH2 column mounting scheme. b) RICH2 hitmap seen from the back of the detector in the first LHCb proton-proton collisions run on 23rd November 2009. This is an accumulated hitmap of all 148 events in the run. c) Hitmap of the 87th event from the same run. Some candidates for Cherenkov rings are seen.

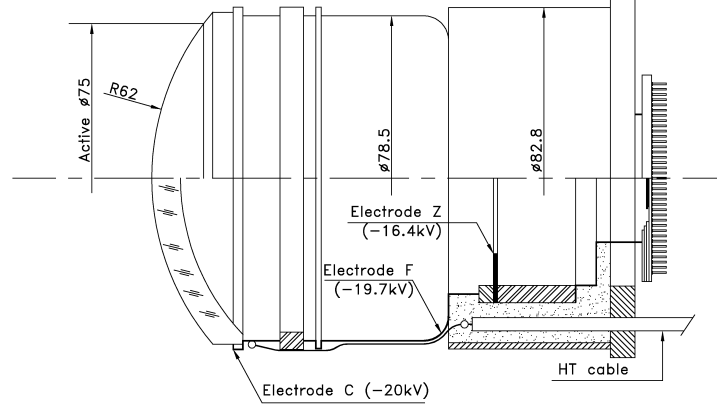


Figure 2.3. Outline drawing of the Pixel HPD [13].

is demagnified by a factor ~ 5 before reaching the anode due to the electrostatic cross-focusing. The radial coordinate at the anode, r_a , is related to the coordinate at the cathode window, r_c , by [13]

$$r_a = 0.200r_c - (4 \times 10^{-4})r_c^2. \quad (2.1)$$

The silicon pixel detector at the anode is segmented into 2^{13} pixels forming a matrix of 256×32 cells. In standard (PHYSICS) operating mode eight pixels are logically ORed into a 32×32 matrix giving cells of a size $500 \mu\text{m} \times 500 \mu\text{m}$ each, with a demagnification of ~ 5 this corresponds to approximately $2.5 \text{ mm} \times 2.5 \text{ mm}$ granularity at the photocathode [21]. Then taking into account the lens effect of the entrance window one can find that this corresponds to $2.82 \text{ mm} \times 2.82 \text{ mm}$ at the periphery.

2.2.1 Semiconductors

Two essential parts of an HPD are the photocathode and the silicon anode, which both are based on semiconductors. A basic introduction to semiconductor physics is presented in Appendix Section A.

2.2.2 Photocathode

The RICH HPD photocathode is of the thin-S20 multi-alkali type (material composition SbNa_2KCs) and is deposited on the quartz window inner vacuum surface [5]. It is mainly composed of semiconducting photo-emissive materials. The operation of a photocathode is based on the photoelectric emission effect, which for

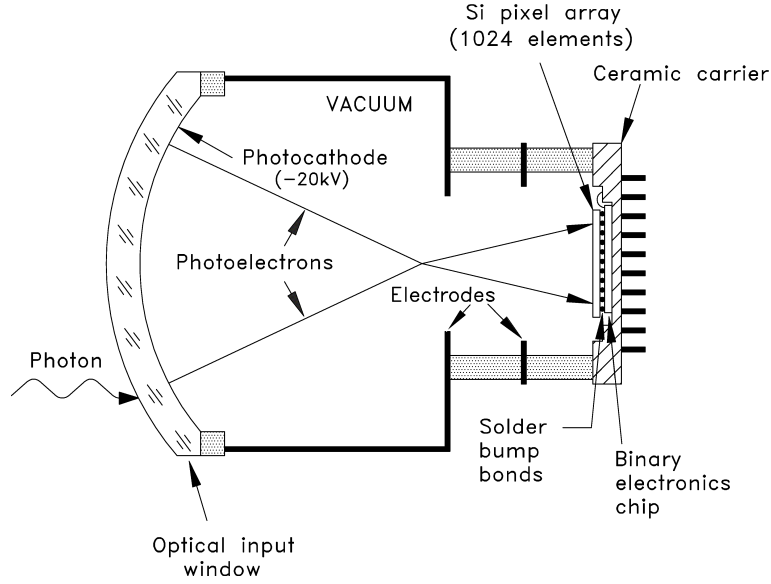


Figure 2.4. Schematic of the Pixel HPD, illustrating photoelectron trajectories [13].

semiconductors may be considered as a three-step process [22]. The first step is where photoelectrons are excited from the valence band to the vacuum level by photon absorption in a thin semiconductor film. The next step is to transport the excited electrons through the semiconductor film to the semiconductor-vacuum interface. The last step is to escape over the surface barrier from the photocathode into the vacuum, this barrier is produced by restraining electrostatic forces present at the photocathode-vacuum interface. All three steps involve energy losses and the efficiency of the photoelectric emission is determined by the efficiency of all three steps. In the first step energy is lost by imperfect absorption of light within the absorption band of the photocathode because of light reflection and transmission. During the transportation step energy is lost by collision with the lattice. In the last step, when the photoelectron escapes into the vacuum, there are surface barrier losses. For example due to the fact that the velocity of the electron is not perpendicular to the photocathode-vacuum interface and therefore not all kinetic energy is used to overcome the barrier.

The photoelectric emission effect for a photocathode can be explained with the energy band model for semiconductors (Fig. 2.5). The valence band, E_V , is completely filled with electrons while the conduction band, E_C , is empty. The forbidden band, E_G , separates E_C from E_V and is defined as the energy difference between the bottom of the conduction band and the top of the valence band. The Fermi level, E_F , lies in the forbidden zone. A photoelectron excited from the valence band to the conduction band can only escape the photocathode if it has enough kinetic energy to overcome the photocathode-vacuum surface barrier, this

energy is the electron affinity, E_A . Photoemission may therefore only occur if the absorbed photon energy, E_p , is greater than

$$\phi_0 = E_A + E_G. \quad (2.2)$$

ϕ_0 is referred to as the photoelectric work function of the photocathode. The energy $E_\gamma = h\nu$ (where h is Planck's constant and ν is the frequency of the radiation) of a photon absorbed by the photocathode needs to exceed the photocathode work function, for a photoelectron having a probability to escape.

A photocathode should have such a composition that the work function is low. The S20 multi-alkali photocathode is a p-type (positively doped) sodium, potassium and antimony semiconducting compound coated with a layer of cesium, this composition causes the bands in the semiconductor model to bend downward close to the surface (Fig. 2.5). Downward bending reduces the effective value of the electron affinity and hence aids the photoemission by lowering the work function.

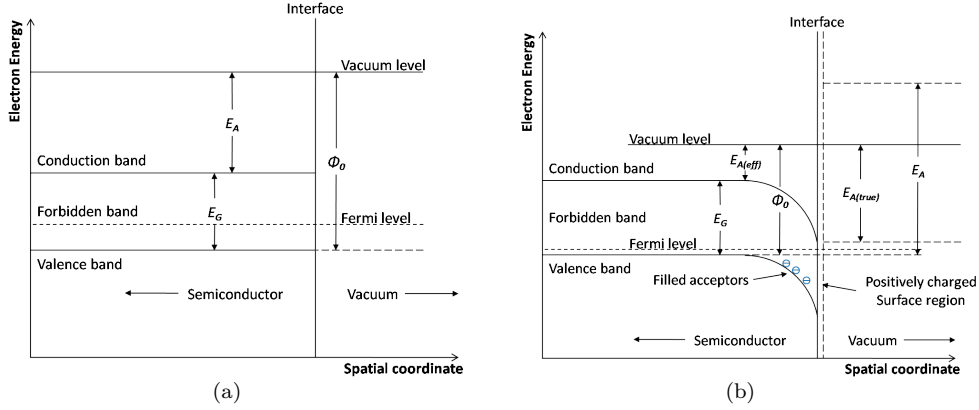


Figure 2.5. a) The semiconductor energy band model. b) The energy band model of a multi-alkali photocathode, where the true electron affinity is reduced close to the surface due to band bending [22].

The photocathode work function of S20 is approximately 1.4 eV [23] which means that the incoming light must have a wavelength lower than around 900 nm to have a probability of being detected. The number of released photoelectrons is proportional to the incident photon intensity. There is also a lower limit on the wavelength of incident detectable light around 200 nm because of the transmission range of the quartz window. The maximum kinetic energy of a photoelectron released is

$$E_{max} = h\nu - \phi_0. \quad (2.3)$$

Since most electrons suffer from collision losses inside the photocathode their kinetic energy can be reduced to range between E_{max} and zero for all incident photon energies.

An important property of the photocathode is the quantum efficiency $QE(E_\gamma)$ which is defined as the fraction of emitted photoelectrons related to the number of photons incident on the photocathode, as a function of light energy (or equivalently light wavelength). It is a property that describes the spectral response of the photocathode and can be given by the formula

$$QE(E_\gamma) = \frac{N_{pe}}{N_\gamma}(E_\gamma). \quad (2.4)$$

N_{pe} is the number of released photoelectrons and N_γ the number of incident photons, this as a function of light energy. The quantum efficiency is usually plotted as a function of wavelength and the multi-alkali S20 used in the RICH HPDs has a maximum of around 30 % and a range between 200 - 900 nm (Fig. 2.6). To get a reasonably good quantum efficiency the photocathode should be of optimal thickness and the composition must be of low work function so that photon absorption is balanced with electron emission.

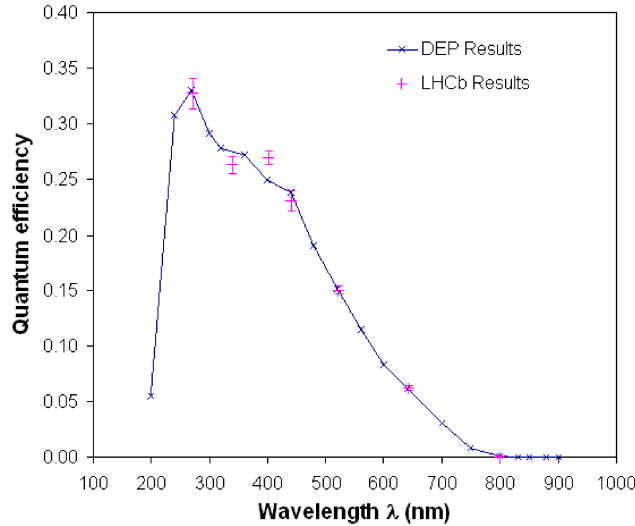


Figure 2.6. QE measurement for one of the best LHCb HPDs made by both the manufacturer DEP and LHCb [5].

In addition to photoemission, photocathodes also produce thermionic emission that is emission of photoelectrons induced by heat in form of thermal radiation. The magnitude of the thermionic emission is determined by the thermionic work function of the photocathode, which is the energy difference between the vacuum level and the Fermi level in the energy-band model. The emission can be further increased by biasing the photocathode with negative voltage relative to its surrounding. The electric field that arises in the photocathode lowers the work function and hence increases the emission current, this phenomenon is known as the Schottky effect. For an HPD thermionic emission is usually included in the

dark count rate, that is the number of detected photons in a certain time without any known external signal source.

2.2.3 Silicon anode

As mentioned previously the incoming photoelectrons strike the surface of a silicon pixel sensor located at the anode of the HPD tubes. Each pixel on the sensor is connected through solder bump-bonding to a readout cell with matching dimensions on the front-end pixel readout chip. The detection efficiency of a photoelectron emitted from the photocathode into the tube vacuum is depending on the silicon anode properties and should be above the LHCb specification of 85 %. Measured values amount to ~ 88 % [19].

Silicon sensor

The silicon sensor has been fabricated by Canberra, Belgium, and consists of a matrix of planar p-i-n diodes which are formed by the union of a p-doped silicon and a n-doped silicon, separated by a thin layer of intrinsic high-resistance silicon [20]. This geometry gives an electric field between the p - and n-type regions that stretches across the middle intrinsic resistive region. During operation the silicon sensor is reverse-biased (normally with 80 V), the p-type is negative to the n-type. The reverse-bias provides a better charge collection than normal bias which reduces the depletion depth and increases the electronic noise. Photoelectrons in the 10 keV range penetrate only a few microns into a diode and hence dissipate their energy close to the diode surface. Free electrons and holes are created and transported to corresponding electrodes at the contact layers on either diode surface. The depletion depth depends on the applied bias voltage and should ideally extend up to the thin contact layers at both diode surfaces. The capacitance of the p-i-n diode is dependent on the depletion depth and hence also on the bias voltage. Full or slight over-depletion by higher bias voltages decreases the diode's noise and improves its efficiency but a strong over-depletion will increase the diode's leakage current and the risk of breakdown. The best operating conditions for an HPD is achieved by slightly over-depleting the diode.

The leakage current consists of a fluctuating current that flows through the ideally non-conducting silicon junctions when the bias voltage is applied, it contributes to the electronic noise of the silicon diode. It is a result of recombination between electrons and holes via trapping centers located within the forbidden energy gap between valence and conduction band. The trapping centers are induced as additional energy levels, either because of impurities of the silicon or by structural crystal defects due to radiation damage. Leakage current is typically within the range of 1 and 100 nA, depending on the size of the diode and the applied bias voltage.

The average energy to create an electron-hole pair in the diodes is $\eta = 3.6$ eV. Neglecting energy losses of photoelectrons within the thin contact layer at the diode surface, charge collection inefficiencies, and the losses due to backscattered

photoelectrons, we can calculate the gain of an HPD by the formula

$$G = \frac{eU}{\eta}. \quad (2.5)$$

e is the electron charge and U the applied voltage difference between photocathode and anode, with nominal operating voltage of 20 kV we get a gain of $G = \frac{1 \cdot 20\,000}{3.6} \approx 5600$. In other words one photoelectron will generate a signal of 5600 electrons in the pixel sensor, in reality the real signal will be ~ 5000 electrons because of the energy losses.

Pixel chip

The LHCb pixel chip, LHCbPIX1 (Fig. 2.7) [21], has been developed by the LHCb collaboration especially for the RICH HPDs. The chip has been designed using special layout techniques to enhance its resistance to radiation. The chip is comprised of super-pixels with dimension $500\,\mu\text{m} \times 500\,\mu\text{m}$, arranged as a 32×32 matrix [21]. These super-pixels are divided into 8 pixel cells of $62.5\,\mu\text{m} \times 500\,\mu\text{m}$ and the pixel chip can work in two different modes with different granularity. In ALICE mode the matrix of 256×32 cells is read out as individual cells, whereas in LHCb mode (which is also called PHYSICS mode since it is the standard operating mode in the LHCb experiment) 8 cells are logically ORed to form a superpixel and hence give a matrix of 32×32 cells (Fig. 2.8). Signals from the silicon sensor are amplified, shaped and compared with a global threshold. The 32 columns are read out in parallel and the analog behavior of the chip is crucial for a good photon detection efficiency. A photoelectron accelerated with the nominal operating voltage of 20 kV will generate a signal of ~ 5000 electrons in the pixel sensor, this can be reduced to below 2500 electrons by charge sharing between adjacent channels. The discriminator threshold, that is the signal size to which the chip should be sensitive, is on average put to 1200 electrons with a RMS spread of 100 electrons. The threshold can be globally adjusted over the whole pixel matrix in a chip, using a chip setting parameter. A low noise and a uniform threshold are important and measured values typically show a noise of 160 electrons [21]. The LHCb pixel chip has a front-end amplifier pulsing time of 25 ns and the chip is mounted with the silicon sensor into a Pin Grid Array (PGA) carrier, data can be read out from the chip in 800 ns. This PGA is in turn connected to an interface board which is the interface to the readout electronics. The nominal operating clock frequency of the chip is 40 MHz.

Since all anode parts are encapsulated in vacuum they must be compatible with vacuum tube technologies. They must also be able to stand high bakeout temperatures of up to 300°C . A specific fine-pitch bump-bonding process has been developed for this application [24].

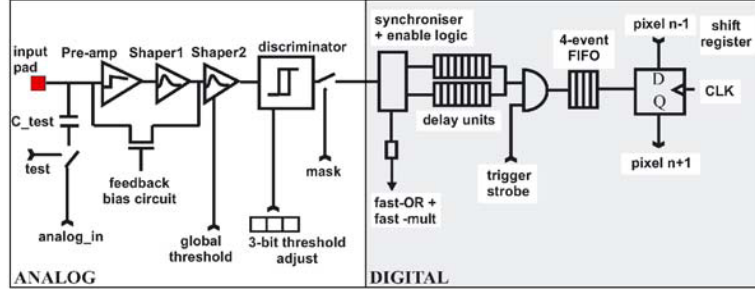


Figure 2.7. Schematic of a pixel cell in the LHCbPIX1 pixel readout chip [21].

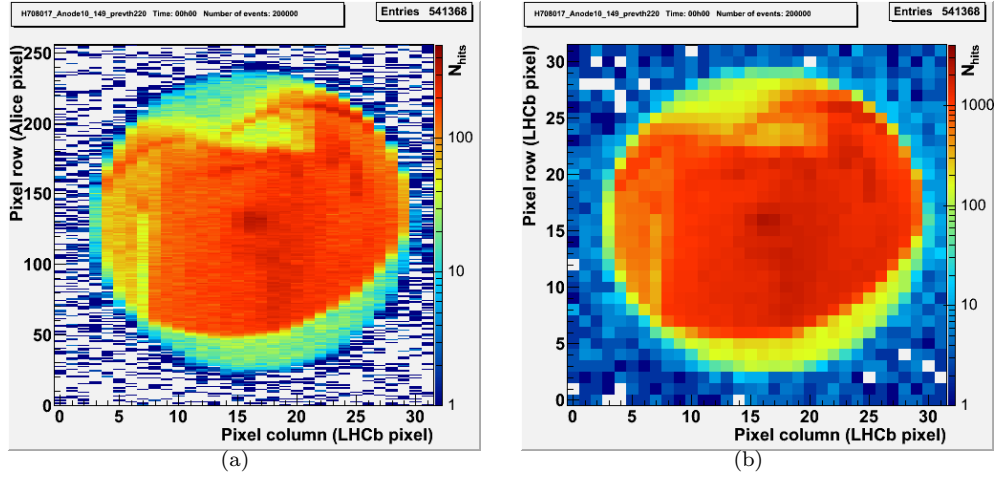


Figure 2.8. a) Hitmap of an HPD in ALICE mode. b) Hitmap of an HPD in LHCb mode.

Backscattering

Energy² striking the silicon sensor has a probability of being backscattered, that is reflected away from the sensor. The reflection is diffuse due to scattering and hence the reflection angle does not need to be equal to the incidence angle. The probability of backscattering to occur is depending on the incidence angle, the atomic number of the sample³, and the incident energy. For the RICH HPDs in operation, the average probability is approximately 18 % [19]. During the backscattering process, energy is transferred to the anode and hence the reflected energy is less than the incident energy. A backscattered photoelectron will move against the applied electric field between the photocathode and the anode, its trajectory depends of the reflection angle and the energy when leaving the anode. It is possible that it will strike the anode at a new position. Photoelectron backscattering is one of the main detection efficiency losses for an HPD.

Charge sharing

Charge sharing is the phenomenon in which a photoelectron deposits its energy not only in the hit pixel, but also in one or more of its neighboring pixels. More precisely, the generated holes in an anode pixel will diffuse during their drift with a probability of reaching adjacent pixels. The fraction of charge sharing in an HPD, with 20 kV applied voltage and a bias voltage of 80 V, is between 15 and 20 % depending on the discriminator threshold [19]. Because of this all adjacent pixel hits are clustered together and assumed to originate from only one photoelectron. This can underestimate the number of photoelectrons if the probability of two photoelectrons hitting the same or adjacent pixels is not zero, this probability depends on the geometrical light profile and the light intensity. Charge sharing in combination with backscattering can lead to further detection efficiency losses. In example consider a backscattered photoelectron which deposits energy of a 2000 e signal into the silicon anode⁴ and the discriminator threshold is 1200 e. If the full signal is deposited in one pixel it will be detected, however if shared between two or more pixels, the pixels will get less energy (≤ 1000 e) than the threshold and the photoelectron will be undetected.

Embedded in the charge sharing effect is capacitive coupled crosstalk which diminish the effect.

2.2.4 Readout electronics

The RICH readout electronics system is divided into so-called Level-0 (L0) and Level-1 (L1) regions. The system reads binary data from the HPDs in the two RICHes, a total of approximately 5×10^5 channels [5].

²in form of a moving photoelectron inside an HPD

³the atomic number of silicon is $Z = 14$ [8]

⁴compare with a normal signal of ~ 5000 e

L0 system

The L0 electronics comprises the pixel chip, ZIFs/kaptons, L0 board and LV/HV distribution. The system is located on-detector and must therefore contain only radiation-qualified components. Signals to and from the HPD pass through the pins of the ceramic PGA carrier which is plugged into a Zero-Insertion-Force (ZIF) connector mounted on a small circuit board. Two Kapton cables transmit signals further, these cables also supply the HPD with low voltage.

The L0 board is an interface between the HPD and the control and data transmission systems of the detector. Its main tasks are to receive data from two HPDs, add headers containing event information and data-integrity checks, and transfer events to the data transmission system. Data from the HPDs is converted into optical signals and transmitted through two output fibers, one per HPD. On the board is a TTCrx⁵ which generates the 40 MHz clock and trigger - and calibration signals. There is also a chip which generates reference voltages required by the HPDs and digitizes monitoring signals such as the temperature of the board as measured by sensors. Since one L0 board interfaces to a pair of HPDs, 242 boards are required for both RICH detectors.

The voltage distribution system is divided into LV and HV systems. The LV system supplies the low voltages required by the L0 boards and the HPDs, it consists of linear voltage regulators mounted on LV boards locally. Each LV board can power two L0 boards independently, and four LV boards are daisy-chained together in an HPD column. The HV system provides the high voltages for the HPDs and one supply unit powers a half HPD column. Resistive dividers derive the three voltage levels of an HPD (photocathode and the two electrodes) and 1 Gohm resistors are used in series with each voltage line to prevent short circuit.

L1 system

The L1 electronics is located off-detector, it implements data compression and serves as an interface between the custom data transmission protocol of the L0 electronics and the industry-standard Gbit Ethernet protocol used by the DAQ (data acquisition) network. It also isolates the DAQ network from errors induced in the L0 data due to radiation induced single event upsets. Incoming serial data is first converted from optical to electrical and then deserialised, further data processing is made in Field-Programmable Gate Array (FPGA) programmable logic. The L1 system is controlled by signals broadcast synchronously to all LHCb subdetectors, the signals are used to control the generation of the data packets sent by the L1 to the DAQ network. The data content of these packets is extracted from the incoming L0 data frames, which have been zero-suppressed (keeping only non-zero bytes). The L1 modules can each receive data from a maximum of 36 HPDs and operate at 1 MHz.

⁵Timing, Trigger and Control Receiver integrated circuit for LHC Detectors

2.3 HPD characteristics

Analyzing the performance of a pixel HPD tube is done by looking at different characteristics, this can be done for example during operation or by specific measurements. Example of characteristics are: Quantum efficiency at different wavelengths, leakage current, number of dead pixels on the chip, electric noise in the chip, photocathode radius, dark count rate. If an HPD in operation is too poor in some respect it will be replaced as soon as possible. One of the most important characteristics of an HPD is the vacuum quality, measured by a quantity called Ion Feedback rate. This will be discussed in the following chapter and is the most common reason of rejecting an HPD.

2.3.1 Photocathode sensitivity

The photocathode sensitivity is the same as the quantum efficiency (QE) mentioned earlier (Eq. 2.4). The QE is obtained by measuring the radiant sensitivity S_R and use the formula [22]

$$\text{QE} = 1.24 \cdot 10^5 \frac{S_R}{\lambda} \quad (2.6)$$

where the QE is in percent, S_R in $\frac{\text{A}}{\text{W}}$ and λ in nm. The spectral radiant sensitivity may be measured by illuminating the photocathode through a narrow bandpass filter with a tungsten lamp. A more accurate method however is to use a monochromator, which is an optical device that transmits a mechanically-selectable narrow band of wavelengths of light chosen from a wider range of wavelengths available at the input.

RICH HPD specifications require that the QE value at 270 nm (approximately the wavelength where the QE is highest) should be at minimum 20 %, HPD testing has given an average value of 31 % for the RICH HPDs.

2.3.2 Dark count rate

The dark count rate is a measure of background signals from the detector, including the electronics, with no known external signal source. These signals are mainly due to thermionic emission from the photocathode, noise signals originating in the electronics chain, signals from cosmic ray particles creating either scintillation in the gas or Cherenkov radiation in the entrance window and also light leaking from the lasers in the readout system, the Gigabit Optical Transmitters.

The value is given in kHz cm^{-2} and is usually measured by taking the number of triggers during a certain time period or by measuring the time for a certain number of triggers. The specification value for the RICH HPDs is a dark count rate of lower than 5 kHz cm^{-2} which is fulfilled by most tested HPDs (Fig. 2.9).

2.3.3 Ion Feedback

Ion Feedback (IFB) is produced by positive ions striking the photocathode surface and there producing a number of secondary photoelectrons. These photoelectrons

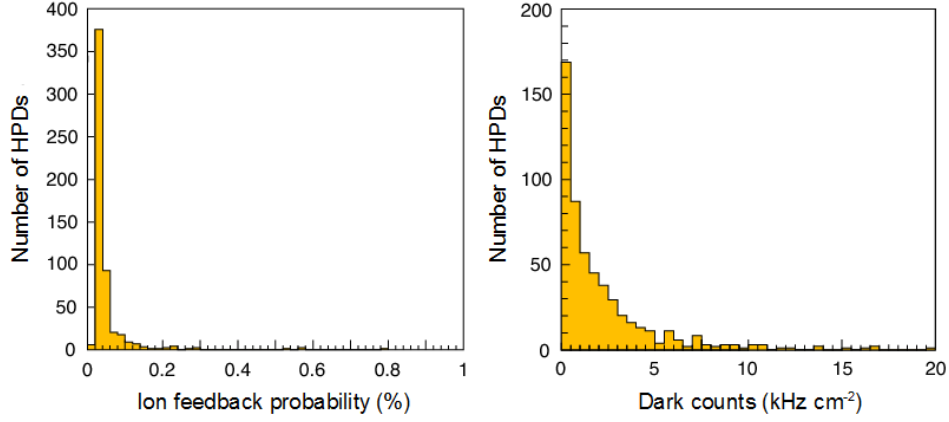


Figure 2.9. Distributions of the IFB rates (left) and of the dark count rates (right) for the LHCb HPDs [5].

are detected 200 - 300 ns after the primary photon signal and come in clusters of 10 - 40 electrons. The ions may have been generated by different mechanisms in a tube, such as photoelectrons colliding with free gas molecules in a vacuum-degraded HPD or photoelectrons bombarding alkali atoms and molecules absorbed on tube surfaces. To measure Ion Feedback an HPD has a property known as the IFB rate, this is an important property which changes in time and has to be monitored for every HPD. The reason is that an HPD with a too high IFB rate will degrade and eventually become unusable. IFB rate is measured in probability, a distribution of the IFB rates for the RICH HPDs is seen in Fig. 2.9. IFB will be further discussed in Chapter 3.

2.3.4 Spatial and time resolution

The resolution of an HPD can be divided into spatial resolution and time resolution. The spatial resolution has been discussed before and depends on the granularity of the pixel chip which for the RICH HPDs gives a granularity of $2.5 \times 2.5 \text{ mm}^2$ at the photocathode. The time resolution of an HPD should be consistent with the LHC bunch crossing rate of 40 MHz, accordingly the pixel-HPD performs a fast 25 ns readout.

2.3.5 Image distortion

The RICH HPDs operate in the fringe field of the LHCb dipole magnet, a magnetic field distorts the trajectory of a photoelectron inside an HPD and hence also the recorded image (Fig. 2.10). All HPDs are individually shielded by high-permeability cylinders and the HPD boxes are surrounded by iron shields, still there are residual stray fields in the HPDs which may degrade the precision. Individual correction factors need to be applied for each HPD and the effect of the

magnetic field must be monitored periodically. Distortions are monitored and corrections calculated in dedicated runs with LED patterns, switching the magnet on and off. When the RICH detectors are in operation corrections will be applied offline on the data.

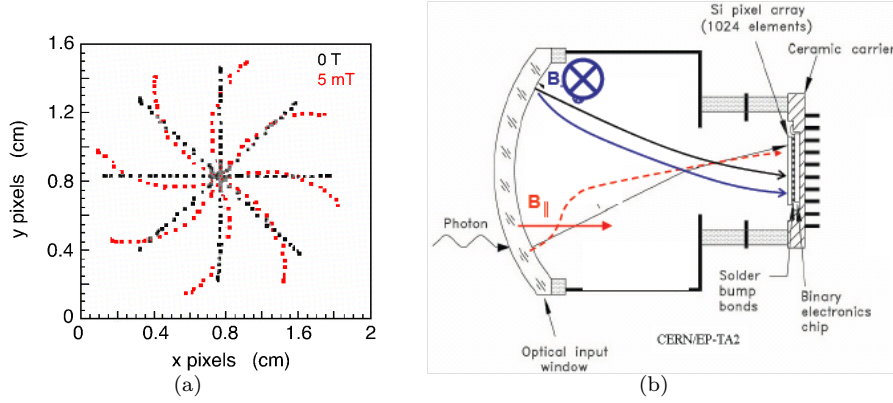


Figure 2.10. a) Image of a star pattern recorded on an HPD with and without a magnetic field of 5 mT applied parallel to the HPD axis [5]. b) Schematic showing that the image is distorted radially by the orthogonal magnetic field component and rotationally by the parallel magnetic field component.

2.3.6 Signal-to-Noise ratio

A high signal-to-noise ratio is important for finding a good discriminating threshold of the readout chip. As stated before the RICH HPDs have a signal of ~ 5000 electrons and a noise of ~ 160 electrons, the mean discriminator threshold is 1200 electrons with a RMS spread of 100 electrons.

2.3.7 Silicon anode photoelectron detection efficiency

Single photoelectron detection efficiency is the fraction of the number of photoelectrons, emitted from the photocathode into the HPD body, detected by the silicon anode at applied operating voltage⁶. A typical value is 88 % for the LHCb HPDs. The efficiency can be determined using a low intensity LED and calibrate the binary pixel data with an analog back-pulse signal. This signal is measured directly from the back-plane of the silicon detector [25]. From the back-pulse spectrum, the number of photoelectrons per event reaching the silicon detector can be determined. Due to the chip threshold setting and backscattering probability of the photoelectrons, there is a detection efficiency loss in the binary pixel data.

⁶using a lower applied voltage will decrease the photoelectron energy and hence also the detection efficiency

Corrections are applied to the binary pixel data due to charge sharing and missing bump bonds.

Non-working bump bonds between the silicon anode and the pixel chip is seen as dead pixels in the readout, LHCb specifications states that the number of dead pixels seen in an HPD chip should be less than 5 %. However not all signals from photoelectrons hitting an unbonded pixel are completely lost, this because of the resulting electric field distortion and charge sharing effects. Bump bonds can be damaged during the bake-out cycle at $\sim 300^\circ\text{C}$ of the vacuum encapsulation, which is the most critical part of HPD manufacturing. Hence bond structure and bond material must be optimized for a good bonding resistance with respect to this heat cycle. A majority of the RICH HPDs have $> 99\%$ working bump bonds.

A silicon anode can also have noisy pixels, that is pixels which read out a larger number of photoelectron hits than they actually receive. Noisy pixels can be excluded by using a mask in the pixel chip (Fig. 2.7), they will then behave as dead pixels.

A too high leakage current in a silicon anode can be a problem for the readout time. The silicon bias 80 V supply is put in series with a $1\text{ M}\Omega$ resistor⁷ and a part of the voltage drop will be in the leakage current. For most anodes the leakage current is small enough for this to be neglected, however if the leakage current is large it will affect the voltage drop over the anode. For example a leakage current of $10\text{ }\mu\text{A}$ in a series of $1\text{ M}\Omega$ resistance will according to Ohm's law have a voltage drop of 10 V, such a current would decrease the true voltage drop over the silicon anode to 70 V. This will increase the transit time of the free charge carriers in the diode (Table 2.1) and misalign the readout in time. This is a problem especially if two HPDs on the same L0 board have a large difference in leakage current since the readout time is adjusted per L0 board, but can not be adjusted per individual HPD.

Table 2.1. Calculated transit time t of a silicon pixel detector reverse-biased at a voltage U [26].

U [V]	t [ns]
21	174
55	36
90	21

⁷for protection against diode breakdown

Chapter 3

HPD ageing effects

3.1 Introduction

The LHCb pixel HPDs are vacuum tubes, which means that ideally there should be perfect vacuum inside the tube body. This is not possible to achieve, an HPD tube will always have a small amount of residual gas inside. If the amount of residual gas is kept at low level the performance is good. If the level is too high the tube will suffer from high Ion Feedback (IFB). The ultimate consequence of a vacuum degradation in an HPD is emission of glow light. In a fraction of the LHCb HPDs it has been observed a significant increase in IFB rate which is interpreted as an increase in residual gas level, that is a vacuum degradation. Over time degradation could be a problem for the performance of the RICH detectors.

3.2 Ion Feedback

When electrons travel inside a gas there is a probability of ionizing the gas molecules. The kinetic energy of an electron can be transferred to a molecule and cause it to ionize. The higher amount of gas, the greater the probability of ionization and hence a vacuum degradation inside an HPD leads to more ions being created when photoelectrons travel in the tube. Under normal HPD operating conditions and in absence of a magnetic field, negative ions should go to either one of the HPD electrodes or to the anode and be collected, while positive ions drift to the photocathode. Ions hitting the photocathode will result in secondary emission of photoelectrons. These will be detected as a cluster of adjacent pixels on the silicon sensor with a size of typically 10 - 40 ALICE pixels¹. This cluster has a delay of typically 200 - 300 ns with respect to the primary photoelectron signal (Fig. 3.1), due to the drift time of the ion, and is referred to as the after pulse [27].

Observations have lead to the following definitions [28] of IFB for the LHCb HPDs:

¹a photoelectron cluster coming from a photon hit has typically a size of 1 - 2 ALICE pixels

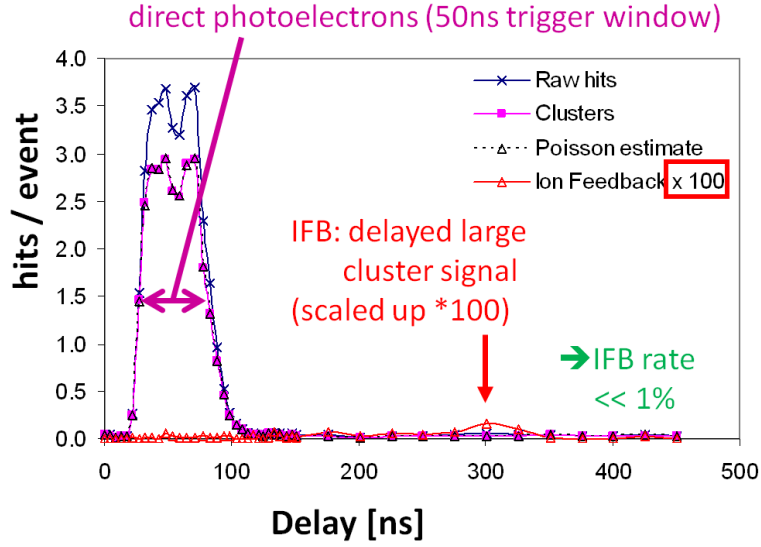


Figure 3.1. Photoelectron response of a low-IFB HPD to a pulsed LED light source with varied delay [27].

Definition 3.1 An IFB cluster is a cluster of five or more (≥ 5) adjacent pixels on the pixel chip, when the chip is read out in ALICE mode (Fig. 3.2).

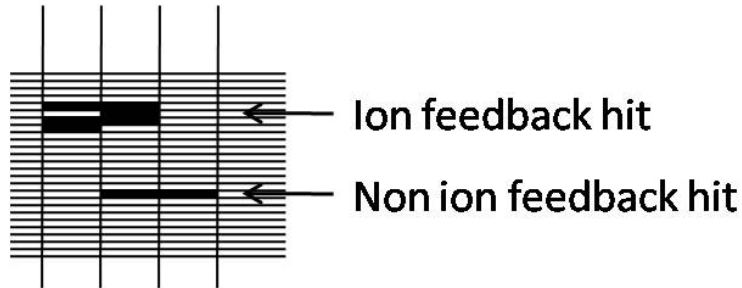


Figure 3.2. An IFB cluster and a non-IFB cluster.

Definition 3.2 The IFB rate of an HPD is the ratio between the number of IFB clusters to the total number of clusters in a run.

The IFB rate is normally given in percent. As the IFB probability is proportional to the concentration of residual gas inside an HPD, it is a sensitive measure of the vacuum quality. It should be noticed that since the cross section of a photoelectron-molecule interaction is energy-dependent, the measured IFB rate in an HPD during

a run is depending on the applied HV². The measured IFB rate will also depend on the light profile, since a concentrated light yields a higher probability of having several adjacent pixels hit by primary photoelectrons. Runs to measure the IFB rate in the RICH detectors are usually done using an HV of 18 kV and a uniform illumination with a continuous laser.

Consider an HPD with an IFB rate I and let the average number of photoelectrons produced by an ion hitting the photocathode and emitted into the HPD body be N_i . The average number of photoelectrons, $\bar{N}$, produced by a single primary photoelectron (including the primary photoelectron) then follows as

$$\bar{N} = 1 + I \cdot N_i + (I \cdot N_i)^2 + (I \cdot N_i)^3 + \dots = \sum_{k=0}^{\infty} (I \cdot N_i)^k = \lim_{k \rightarrow \infty} \frac{1 - (I \cdot N_i)^k}{1 - (I \cdot N_i)}. \quad (3.1)$$

If $|I \cdot N_i| < 1$ the series in Eq. 3.1 converge and $\bar{N}$ is given by

$$\bar{N} = \frac{1}{1 - I \cdot N_i}. \quad (3.2)$$

If the IFB probability multiplied by the average secondary electron yield exceeds unity, $I \cdot N_i > 1$, the IFB effect is self-sustained and the photon current rises exponentially.

3.3 Glow light

A fraction of HPDs, $\sim 10\%$ [28], have been observed to emit light out of their entrance windows when biased with HV, a phenomenon known as glow light. Positive ions hitting the photocathode, recombine with electrons and send out photons as a result (Fig. 3.3). The effect is especially seen during HV ramp up when a tube is in its glowing regime, at high voltages the glow behaviour has been observed to switch off. Glow light is a signature of an extremely large IFB rate and hence it originates from a too large residual gas level in a tube.

Glow light starts to occur in an HPD when $I \cdot N_i > 1$ in Eq. 3.1. There is no specific threshold in IFB rate for when an HPD starts glowing, variations are observed from tube to tube. The threshold is when

$$I \cdot N_i = 1 \quad (3.3)$$

where N_i is depending on the photocathode properties. The integrated IFB limit for an HPD to be in the risk zone of start glowing is put to 5 %. No tube has been seen glowing with an IFB rate less than 5 % whereas it generally starts soon after this limit has been passed. Using a limit of 5 % in Eq. 3.3 yields $N_i = 20$ released photoelectrons in an IFB cluster.

²the detection efficiency of photoelectrons in the silicon anode is also depending on the HV

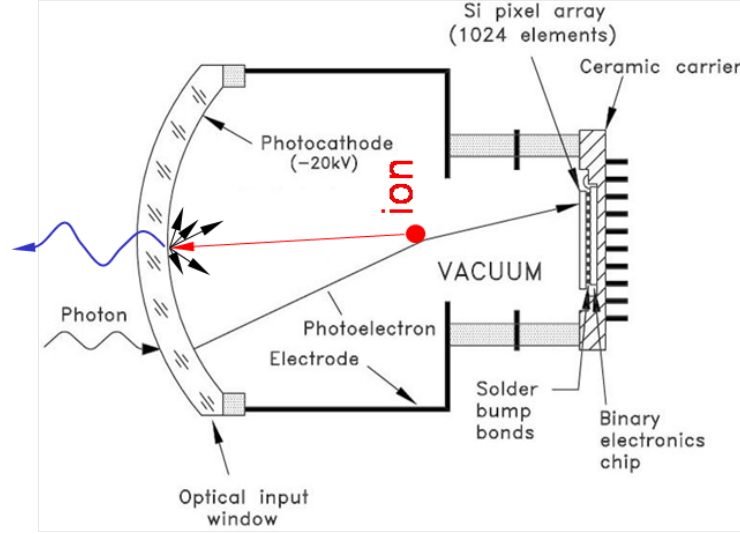


Figure 3.3. Schematic showing how a photon is emitted from the photocathode when struck by an ion.

3.3.1 Glow light in the RICH detectors

Glow light and IFB signals can cause problems for the LHCb RICH detectors, both for the physics performance but also for the operation of the detectors. HPDs with self-sustained IFB become unusable for data acquisition as they produce huge amount of noise. In addition other HPDs on the same column are disturbed by the excess current in the silicon bias, since they share the same bias voltage supply. A glowing HPD should be removed as soon as possible from the detector, and ideally be replaced by a better functioning tube. The number of spare tubes available and the access to the detector are the limiting factors in this respect. It can even be favorable to replace a glowing HPD by an anode, there will be an empty space in the detector but the shared silicon bias supply will be less disturbed.

Glowing HPDs are recognized by the bright spots at the center of the photocathode image in the RICH detectors (Fig. 3.4). They are also detected through the HPD photocurrent which reaches saturation. The saturation level is determined by the silicon bias voltage and the 1 M Ω limiting series resistor in the silicon bias supply circuitry.

3.3.2 Glow light in dark room

Even though not exposed to an external light source, a glowing HPD will start to emit light when biased with high voltage. Thermal photoelectron emission from the photocathode starts the self-sustained IFB effect. To get a qualitative feeling of how strong the light emission is and where it is from, an HV ramp up was performed in a dark room. Photographing the biased HPD with a fixed camera

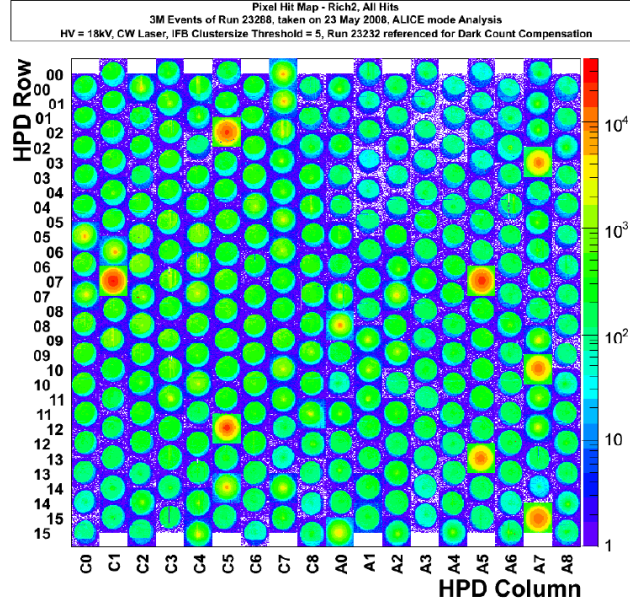


Figure 3.4. Hitmap from a run with laser in RICH 2 with some obvious glowing HPDs [29].

and long exposure time, a picture of the faint glow light was taken (Fig. 3.5). From the photo it is clear that most of the light emission is at the central axis of the tube. Taking a similar photo with the HPD exposed to an external magnetic field made the light spot move, therefore the light emission must originate from charged particles, ions.

3.3.3 Ion annealing

The glow light effect has been observed to decrease, and finally to switch off in some HPDs. This is seen when a glowing HPD in operation is submitted to external illumination for a longer time, but also when keeping a tube biased in the glowing regime without external illumination. This can be explained by annealing of the residual gas molecules when ions are created and hence the IFB effect is annealing itself. It could also be explained by a degradation of the photocathode. In other words decreasing either I or N_i in Eq. 3.1.

3.3.4 Photocathode degradation

On glowing HPDs removed from the RICH detectors, small discolored spots (in the order of 1 mm in radius) have been visually observed at the center of the entrance windows. The position of the spots coincide with the position of the glow light seen in Fig. 3.5. Measurements of the radial photocathode response have shown a significant drop in quantum efficiency in the central region of glowing

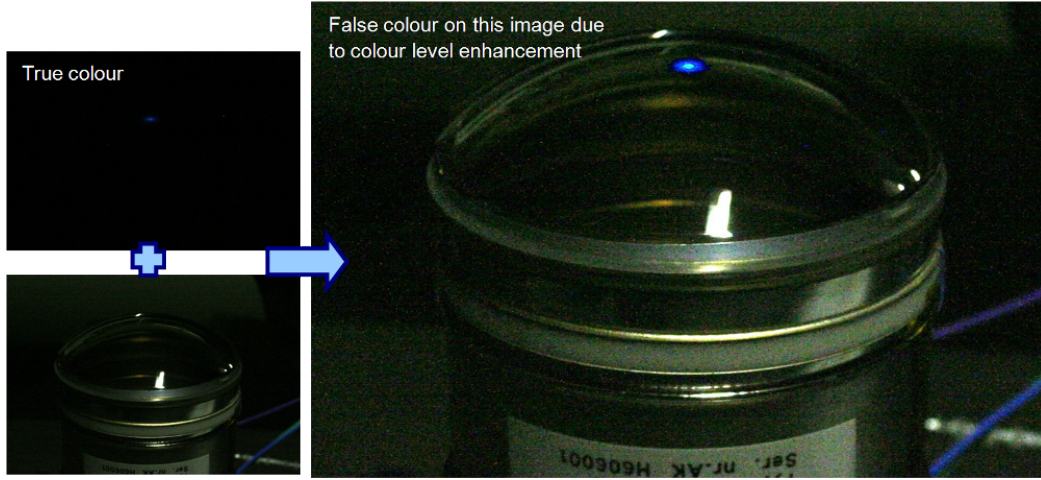


Figure 3.5. Photo of HPD glow light, observed as faint blue light at the center of the quartz window [29]. The top picture on the left hand side is taken in a dark room having the HPD biased with 16 kV, the camera is set in the most light sensitive mode using 30 s integration time. The bottom picture on the left is from the same position but with ambient light on and HV off. The right picture is an overlap of the two where the position of the glow light source is viewed.

HPDs (Fig. 3.6). This shows that the glow light effect degrades the photocathode in the central region which leads to impaired performance of an HPD.

3.3.5 IFB measurement

The IFB rate of an HPD can be measured in two ways: Either with a continuous light source where the integrated IFB rate is estimated, including on average all after-pulse events. The second method is with a pulsed light source and then the maximum IFB rate is estimated by the strobe scan method, where the electronics strobe is delayed with respect to the primary light pulse. In the LHCb RICH detectors the first method is easier to implement and hence preferred, but the two methods are equivalent and their correlation is well established.

The IFB rate in an HPD has been observed to change over time. Investigations show that IFB progression starts from the HPD manufacturing date and most tubes show a linear IFB increase with time and different slopes from HPD to HPD (Fig. 3.7). The evolution of the IFB rate also depends on how much the tube is illuminated. From a total of 550 HPD tubes produced for LHCb, approximately 20 % have started to glow or have a risk of doing it within the coming years. Most of these degraded tubes come from early batches, that is they are among the first ones manufactured for LHCb. A linear model of the IFB progression for each HPD has been developed. This allows estimating future behavior of the HPD. From the model predictions are made to see when individual HPDs will cross the 5 % IFB threshold and enter the risk zone to start glowing. HPD replacement in the RICH

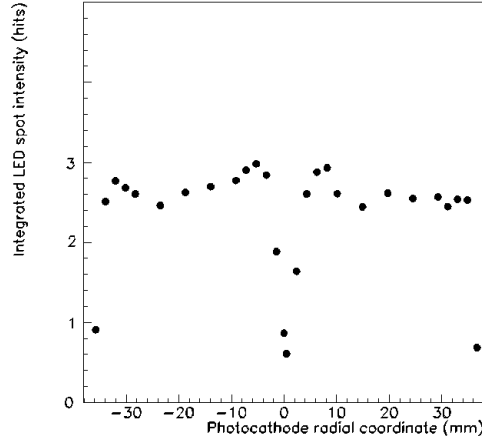


Figure 3.6. Integrated radial photocathode response in a glowing HPD, recorded shortly after the tube was removed from RICH 2 [30].

detectors are based on these predictions. A glowing HPD can be repaired and so far results from HPD reparation have been highly satisfactory.

3.4 Measurements of the HPD glow light

The gradual increase in IFB rate and the glow light effect in an HPD could be caused by a number of different gases. Finding the molecule type of the gas is a step in the investigation. Three main candidates are water vapor (H_2O) outgassing from a tube body part, helium (He) permeating through the quartz window and hydrogen (H_2) which is used in the HPD manufacturing process. Doing a spectroscopy of the glow light is a way to get information on the type.

The following HPDs have been subject to measurements:

- **H546003**, seen glowing in February 2008 and removed from RICH 2 in May 2008.
- **H546004**, seen glowing in August 2007 and removed from RICH 2 in January 2008.
- **H549002**, seen glowing in January 2008 and removed from RICH 2 in January 2008.
- **H638005**, low-IFB HPD that is now inside RICH 1 position U0_6.

3.4.1 Spectra with discharge lamp

For comparison purposes, spectral measurements were made using a discharge lamp with electrodes made of tungsten and a monochromator. Different gases were introduced in the lamp and spectrum scans were recorded. The results can

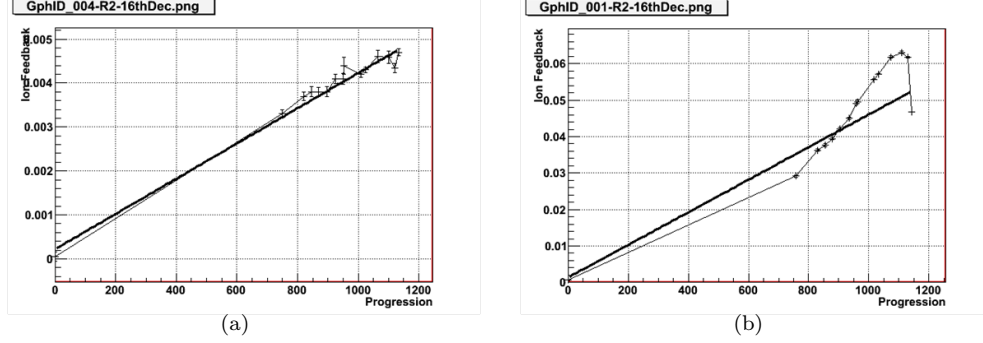


Figure 3.7. a) An HPD showing a slow IFB progression that can be fitted with a straight line [31]. The horizontal axis represents tube age in days, the vertical axis represents IFB rate in probability. b) An HPD showing a fast non-linear IFB progression [31]. At around 1100 days the tube starts to glow and shows a turn-off afterwards due to annealing effects.

be seen in Fig. 3.8. Possible lines at 401 nm, 407 nm and 430 nm can be attributed to tungsten [32].

Spectral lines

Between 200 and 700 nm there are clear helium lines at 389 nm, 403 nm, 447 nm, 471 nm, 492 nm, 502 nm, 588 nm and 668 nm. The main hydrogen lines in the same range are at 410 nm, 434 nm, 486 nm and 656 nm [32]. Notice the absence of continuum in both the helium - and hydrogen spectra.

3.4.2 Experimental setup and protocol

By ramping up HV on an HPD tube in steps, measuring silicon bias current and using a monochromator to select wavelength and a photomultiplier tube³ (PMT) to count photons (Fig. 3.9), it is possible to see if and when glow light turns on in the tube. The monochromator used has a resolution of 1 - 2 nm.

An HPD was put in a light-tight box with no external illumination, only dark counts from the tube itself. The HPD axis was aligned with the entrance slit of the monochromator and a collecting lens in between. The PMT was counting photons at the exit slit of the monochromator (Fig. 3.9). HV bias was made according to the same scheme as used in the RICH detectors. The silicon anode was put in series with a 1 M Ω resistor to prevent breakdown, and reverse-biased with a maximum of 80 V. The bias current was measured indirectly by measuring the voltage drop across an additional 1 M Ω resistor, using the relation 1 μ A $\cong$ 1 V drop.

³model R1635-02 Hamamatsu

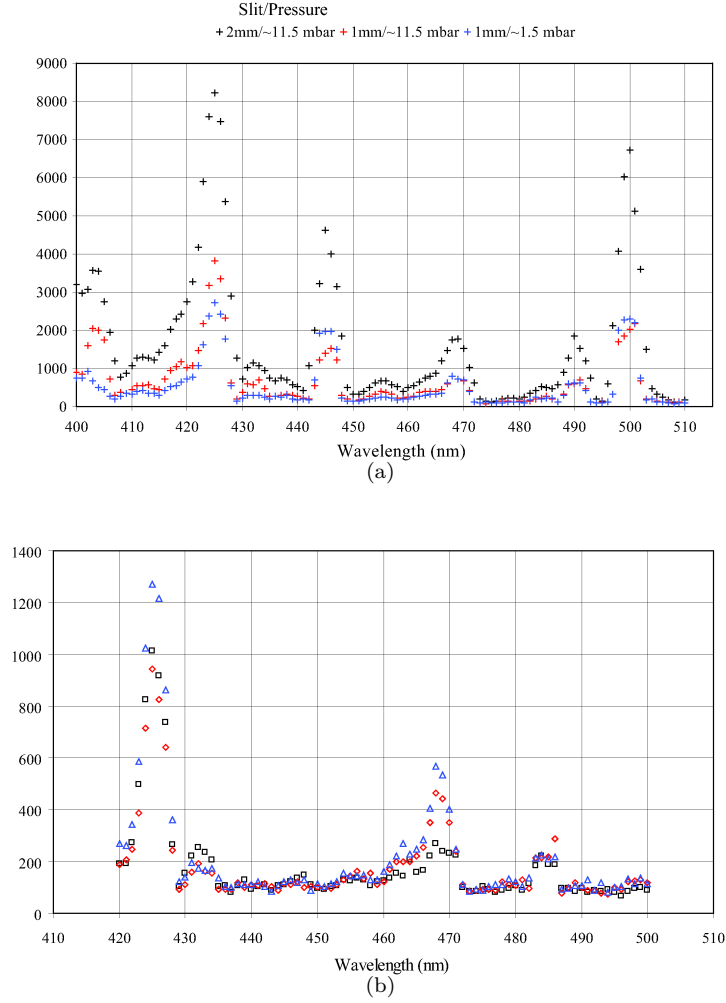


Figure 3.8. a) Spectrum scan with helium in a discharge lamp. There is an offset of about -1.5 nm in the monochromator, i.e. a line at 400 nm will show up at 398.5 nm. The lines at 403, 447, 471, 492 and 502 nm are visible. b) Spectrum scan with water (H_2O) in a discharge lamp. There is an offset of about -1.5 nm in the monochromator. The hydrogen lines at 434 nm and 486 nm are visible.

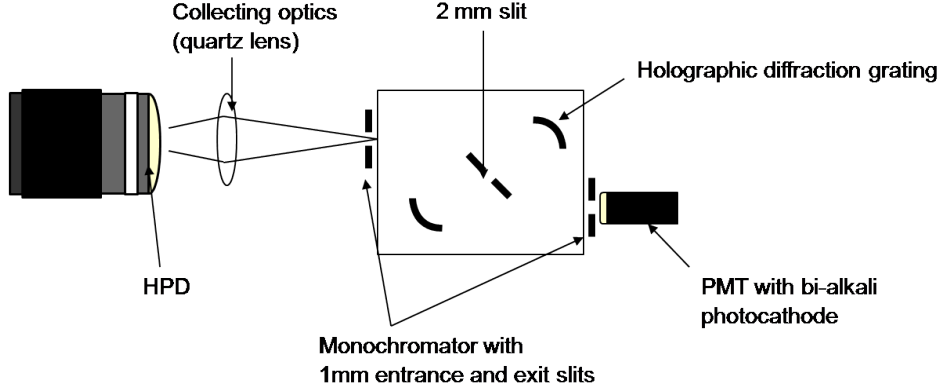


Figure 3.9. Setup for measuring the HPD glow light during ramp up and spectrum measurements.

3.4.3 High Voltage ramp up

The HV was ramped in steps of 500 - 1000 V while measuring the voltage drop over the silicon bias and the HPD glow light photon count at a wavelength of 450 nm for each step. This wavelength was chosen from observations made of the typical glow light intensity being highest close to this wavelength. The bias current, for a glowing HPD, increased with HV until it reached a saturation level depending on the reverse-bias voltage applied on the silicon anode (Fig. 3.10 and Fig. 3.11). The photon count was typically seen to increase with increased HV. For a glowing HPD it was avoided to go all the way up to the nominal operating voltage of 20 kV, discharges (coronas) started to occur around 15 kV with a risk to damage the tube and the measurement devices.

3.4.4 Glow light spectrum scan

After HV ramp up, a glow light spectrum scan was performed. The glow light spectrum and its spectral lines are useful information when trying to determine the ion types. By knowing the ion types, candidates for molecules causing the vacuum degradation can be suggested and give hints of how the vacuum degradation has been introduced.

The scan was made by a computer-controlled setup, changing the transmitted wavelength of the monochromator in steps of 1 nm or larger and using an integration time of typically 60 s per step. The scanned wavelengths were typically in the range of 200 to 700 nm, that is the range where both the HPD - and PMT quantum efficiencies are non-zero. The reproducibility in wavelength from the monochromator is ≤ 2 nm, and the standard deviation in number of photon counts from the PMT was put to the Poisson error, i.e. $\sqrt{N_{counts}}$, under the assumption that the measured count rate comes from a random Poisson process.

The glow light spectrum typically shows two wide features with peaks around 330 nm and 450 nm respectively (Fig. 3.12). There is one clearly identifiable

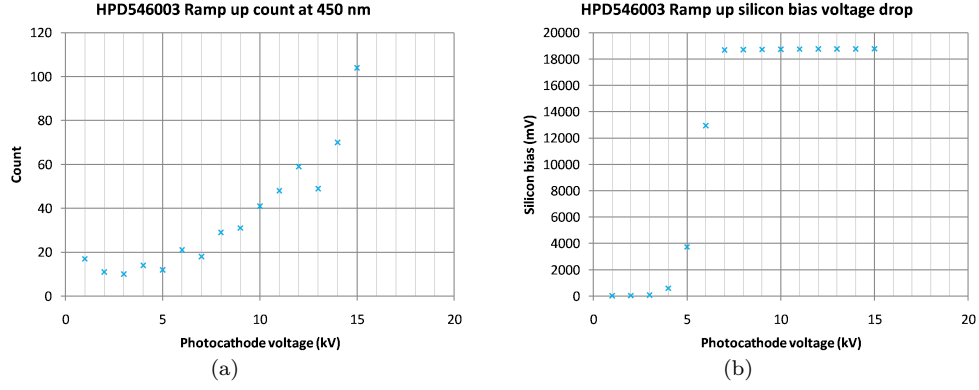


Figure 3.10. HV ramp up on H546003 having the silicon anode reverse-biased with 40 V. The IFB effect was seen in the silicon bias at 5 kV while the PMT started detecting glow light around 8 kV. a) Photon count at 450 nm as a function of applied HV. b) Voltage drop over the silicon anode as a function of applied HV.

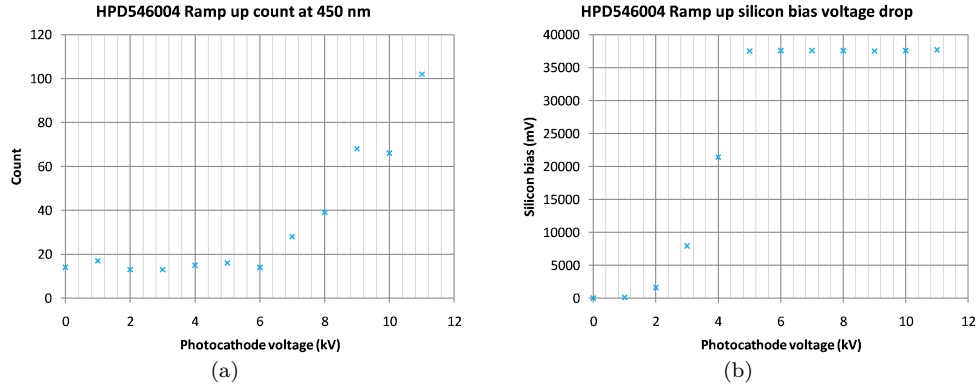
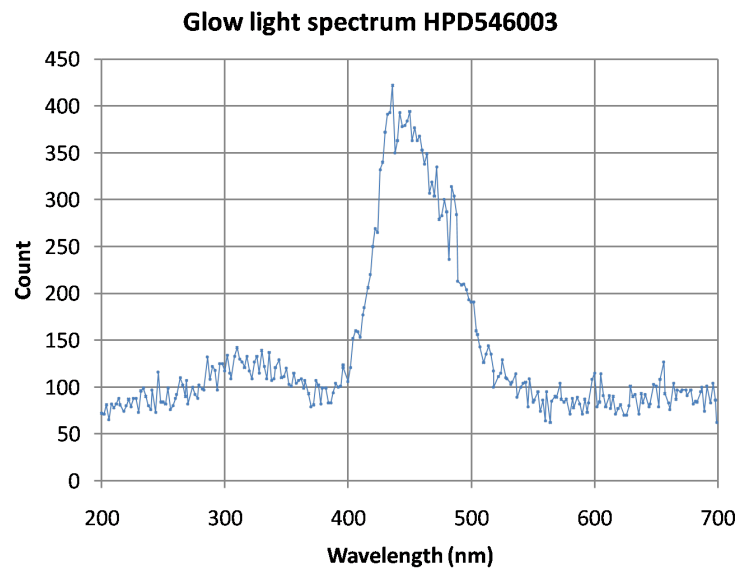
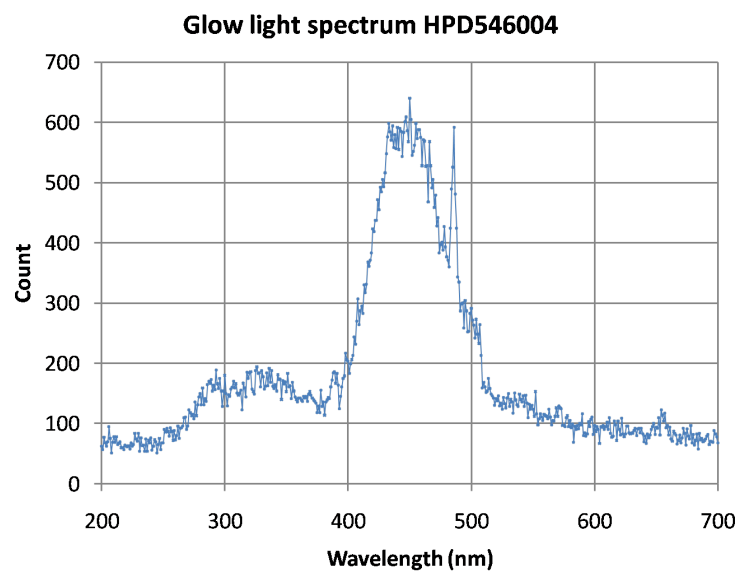


Figure 3.11. HV ramp up on H546004 having the silicon anode reverse-biased with 80 V. The IFB effect was seen in the silicon bias at 3 kV while the PMT started detecting glow light around 7 kV. a) Photon count at 450 nm as a function of applied HV. b) Voltage drop over the silicon anode as a function of applied HV.



(a)



(b)

Figure 3.12. a) Glow light spectrum scan made on H546003, photocathode biased with -11 kV, 60 s integration time and 2 nm steps. b) Glow light spectrum scan made on H546004, photocathode biased with -15 kV, 60 s integration time and 2 nm steps.

spectral line at 486 nm (Ex. 3.1), other candidates for lines are seen at 436 nm and 655 nm. The width of the line at 486 nm is compatible with the monochromator resolution.

To further examine a possible spectral line and estimate its position, the background was subtracted under a linear approximation and the nearby range of the line fitted by a Gaussian. The feature around 655 nm seems to be attributed to a real spectral line, the other candidates are either not strong enough to be outside the errors or just noise (see Appendix Fig. C.1 for fits).

Example 3.1

Using Root (the standard physics software package used at CERN, built upon C++) a fit with the following distribution $p_1 + p_2\lambda + p_3 \exp(-\frac{1}{2}(\frac{\lambda-\mu}{\sigma})^2)$, was made for the data within the range 450 to 520 nm. Root uses a numerical minimization package MINUIT to fit a distribution, MINUIT will try to find the value of the parameters which give the lowest value of chi-square (χ^2) between the fitting function and the given data [33]. It uses the iterative MIGRAD algorithm which is a variable-metric method with inexact line search, a stable metric updating scheme, and checks for positive-definiteness.

The fitted lines in Fig. 3.13 are from converging algorithms, the plots show that the feature is outside errors and hence a real spectral line. The standard deviation, $\sigma \approx 1.5$ nm, agrees with the monochromator resolution.

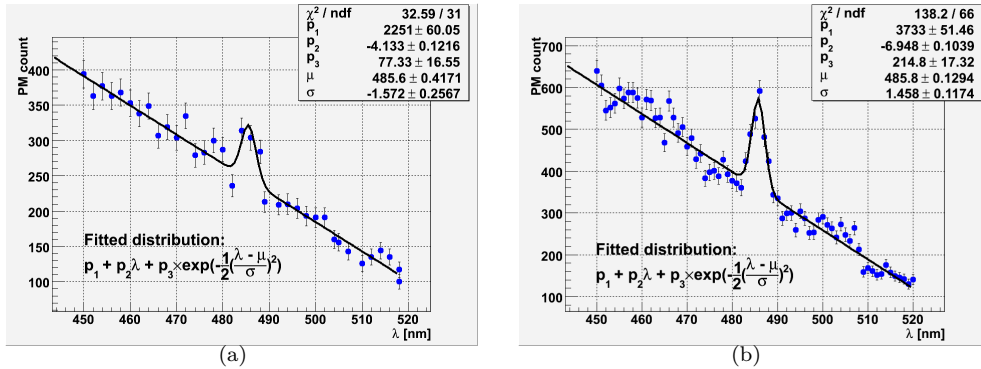


Figure 3.13. a) H546003 glow light spectrum in a zoomed version around 486 nm, plotted with error bars and a fitted distribution. b) H546004 glow light spectrum in a zoomed version around 486 nm, plotted with error bars and a fitted distribution.

3.4.5 Glow light spectrum with mask

In Fig. 3.5 it is seen that visually the glow light is observed on the middle axis of the tube. To confirm this, a glow light spectrum with a mask in front of the HPD entrance window was recorded (Fig. 3.14).

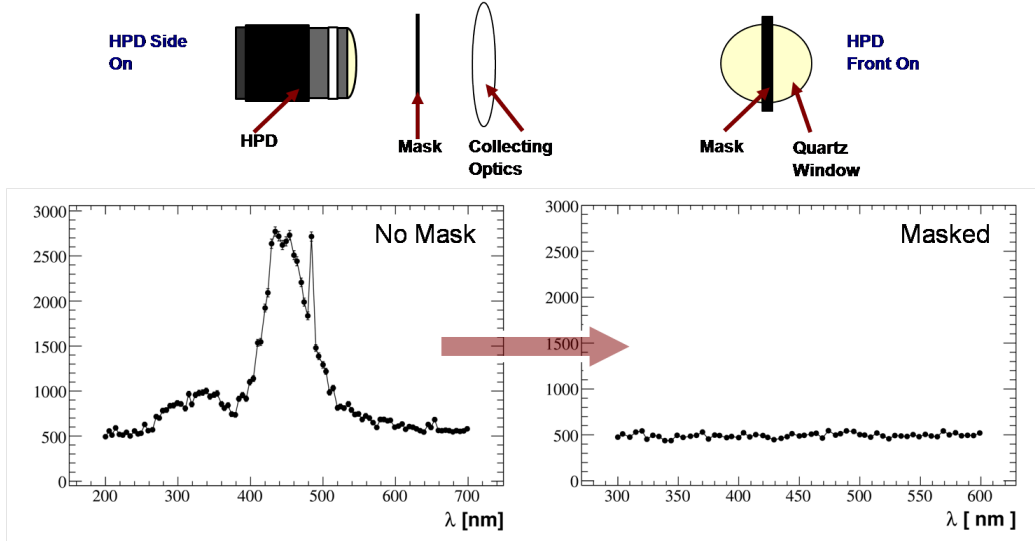


Figure 3.14. Glow light spectrum recorded without and with a mask in front of the center of the HPD. This shows that the glow light effect is concentrated to the central region.

3.4.6 Temperature effects on a glowing HPD

Applying the idea of cooling a glowing HPD, H549002 was left in a climatic chamber at -20°C for $2\frac{1}{2}$ days. Glow light spectrum scans were taken before and after the cooling, when the HPD was back at room temperature. There was a clear reduction in the intensity of the glow spectrum (Fig. 3.15). There was also a later turn-on of glow discharge during HV ramp up.

After cooling, the HPD was left in ambient room temperature for ~ 30 days and then remeasured. The glow light was back at a higher intensity with the same spectrum as before cooling. However after being biased with HV for 30 min the glow behavior switched off. The tube was subsequently put in the climatic chamber at 50°C for $2\frac{1}{2}$ days, after this the glow light returned and was more stable with time.

3.4.7 Conclusions

HPD glow light is normally first detected by an intense spot at the center of the anode together with a strong increase in silicon bias current during operation.

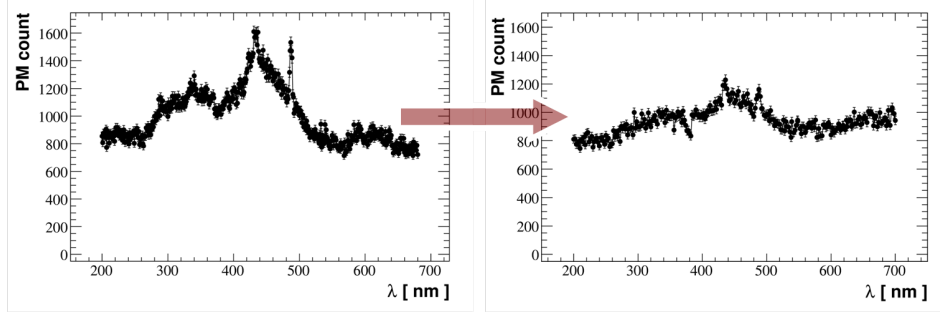


Figure 3.15. Glow light spectrum scan made before (left) and after (right) cooling a glowing HPD for $2\frac{1}{2}$ days at -20°C .

Faint blue light is emitted at the center of the photocathode, at the same position there is a significant degradation in quantum efficiency. This is explained by ion bombardment, knocking out cathode atoms and causing a surface erosion. This erosion is also visually observed as a discolored spot at the entrance window. The glow light intensity, as measured at 450 nm, is seen to increase with increased applied HV.

If the HPD vacuum is high, nothing will happen during operation besides backscattered electrons falling back onto the anode. If the vacuum is degraded, residual gas atoms are present which might become ionized. Ions tend to follow straight electric field lines, therefore the created positive ions will mainly follow the central field line to the photocathode. Consequently a feed-back process has been established.

The IFB signal has a delay of typically 200 - 300 ns with respect to the primary photoelectron signal (Section 3.2). Using the simplified HPD model of Ex. B.2 in Appendix the transit time, t_{trans} , of a charged particle inside an HPD is proportional to $\sqrt{m}$ (Eq. B.8). With 20 kV applied voltage and a distance between the photocathode and the anode of 110 mm, Eq. B.9 yields $t_e \approx 3$ ns for a photoelectron with zero initial kinetic energy. The lightest ion, H^+ (i.e. a proton), has a mass of ~ 1836 times the mass of an electron. The same model estimates its transit time to $t_H \approx 110$ ns. These are very coarse approximations, however if the ions are created close to the anode inside an HPD, a delay of 200 - 300 ns should be consistent with a light ion.

Looking at light spectra of glowing HPDs, two wide features with peaks around 330 nm and 450 nm respectively are observed. The 450 nm feature is dominant in intensity and ranges from around 400 to 510 nm, this is consistent with glow light being visually observed as a faint blue light. These two wide features have not been explained yet, one possible cause could be radiation induced scintillation from the quartz window.

Besides the wide features, the glow light spectra show lines of hydrogen. No lines of helium are observed. Lines could come from H^+ ions picking up electrons from the photocathode and recombining. The most frequently observed rest gases in a

vacuum system are water (H_2O) and hydrogen (H_2). If the restgas was H_2 it is very unlikely that there would be temperature effects on the glow light as observed.

3.5 IV measurements

An IV measurement is a fine scan made on an HPD, measuring the electrodes and anode current (or photocathode current) as a function of applied photocathode voltage. The resulting IV curve gives an indication of the voltage at which the IFB effect starts. This is seen as a sharp change of slope in a curve of a high-IFB HPD, which is not seen in a curve of a low-IFB HPD. Looking at ionization thresholds for different molecules it is then possible to suggest candidates for the molecule causing the effect.

3.5.1 Theoretical IV curve

An IV curve for an HPD would ideally look like in Fig. 3.16. The threshold where the HPD starts detecting photons is depending on the photon energy, which has to be larger than the photocathode workfunction (Eq. 2.3). The main reason for the smooth, rather than immediate, transition to full photocurrent is the velocity spread of the emitted photoelectrons. Possible other reasons are tunneling phenomena and Schottky effects (Section 2.2.2). The slope also depends on the light energy since this energy will determine the range of velocity spread of the emitted photoelectrons.

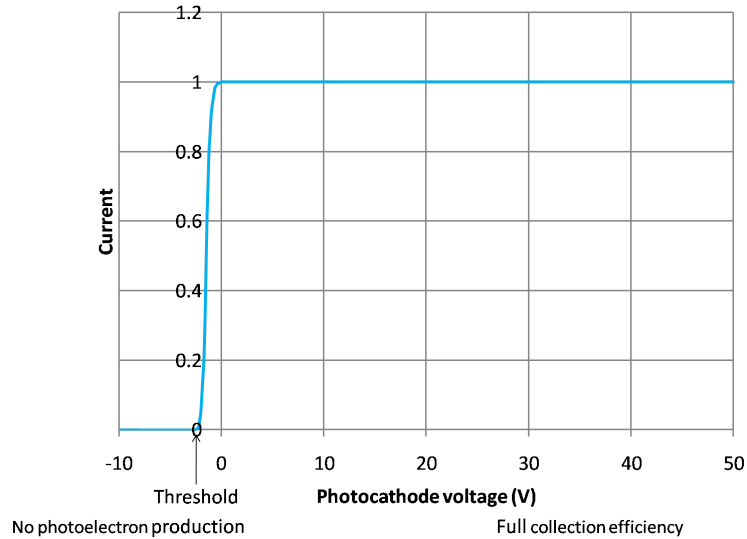


Figure 3.16. The ideal IV curve.

3.5.2 Setup

The setup (Fig. 3.17) consisted of one combined voltage source and ampere meter connected between the photocathode and ground, one ampere meter measuring the photoelectron current on the two electrodes and the anode, and also an LED light source illuminating the HPD entrance window. Two different LEDs were used, a blue LED with a peak wavelength of 470 nm and a red LED with a peak wavelength of 645 nm. The LEDs were illuminating the full photocathode rather than a collimated spot, the LED current was typically adjusted to ~ 1 mA. By changing the applied photocathode voltage in small steps while measuring the current on both the photocathode and the electrodes/anode an IV curve for the HPD was obtained. Normally the current in the photocathode should be equal to the electrodes/anode current since all photoelectrons created at the photocathode should go to either an electrode or to the anode, when the tube is biased. Effects were observed which made it worthwhile to measure both currents, however if not specifically mentioned it is always the electrodes/anode current that is plotted. For simplicity the positive voltage axis in an IV curve corresponds to negatively applied photocathode voltage.

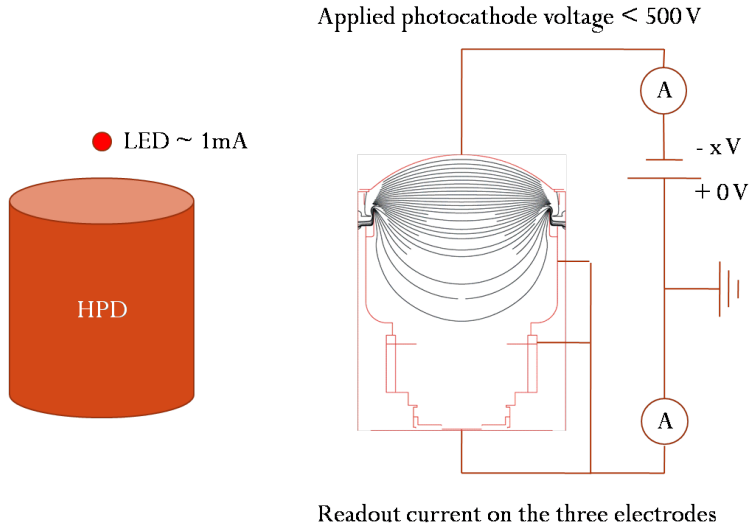


Figure 3.17. IV measurement setup.

3.5.3 Results in a low-IFB HPD

The IV curve of an HPD with perfect vacuum (i.e. no IFB) would only differ from the ideal IV curve due to collection efficiency. Full collection efficiency is reached first at a larger applied voltage and the IV curve is more stretched out. However IFB in an HPD causes the measured IV curve to deviate from the ideal IV

curve significantly. Performing an IV measurement on H638005 (a low-IFB HPD) yielded an IV curve not far away from the ideal one (Fig. 3.18). The curve shows that the HPD starts to detect photons when biased with approximately -0.5 V, that is a positive voltage on the photocathode and hence a retarding electric field inside the tube⁴. The rise to almost full photoelectron collection efficiency is fast and the curve flattens out early, already at 1 V the collection efficiency is almost optimal.

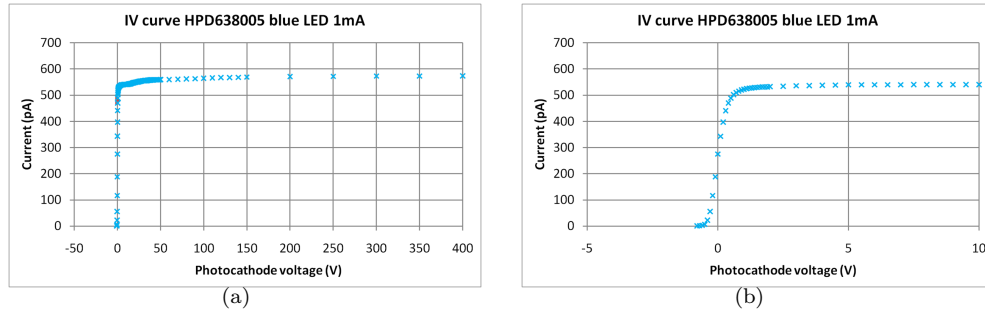


Figure 3.18. a) IV curve for the low-IFB H638005 illuminated by a blue LED. b) The same IV curve in a zoomed version.

3.5.4 Results in two glowing HPDs

The same IV scan was performed on the glowing tubes, H546003 and H546004 (Fig. 3.19). Glow light spectrum scans, made a couple of days before the IV measurements, confirmed the glow light (Fig. 3.12). The strong glow light intensity seen in H546004 implies a high IFB rate in the tube, this conclusion was further enhanced by the IV measurements. A fast drop in readout current over time, when the tube was biased with 120 V or higher, is interpreted as the molecules inside the HPD started to anneal at a quick rate. It could also be a sign of fast photocathode degradation and therefore a decreasing secondary yield.

The IV curves of the two glowing HPDs (Fig. 3.19) look almost the same as for the low-IFB HPD (Fig. 3.18) when limiting the range to low voltages, ≤ 15 V. After this limit there is a sharp change in slope and a fast increase in photoelectron current is observed, this due to the IFB. The effect starts to occur somewhere around 17 V (Fig. 3.20), giving an indication of the threshold for gas ionization inside the tubes being close to 17 eV.

⁴a retarding electric field is achieved in an HPD when a positive voltage is applied to the photocathode relative to the electrodes/anode

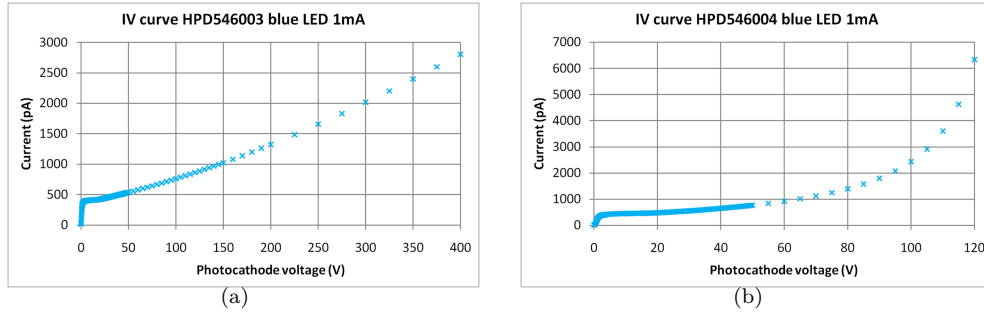


Figure 3.19. a) IV curve for the glowing H546003 illuminated by a blue LED. b) IV curve for the strongly glowing H546004 illuminated by a blue LED.

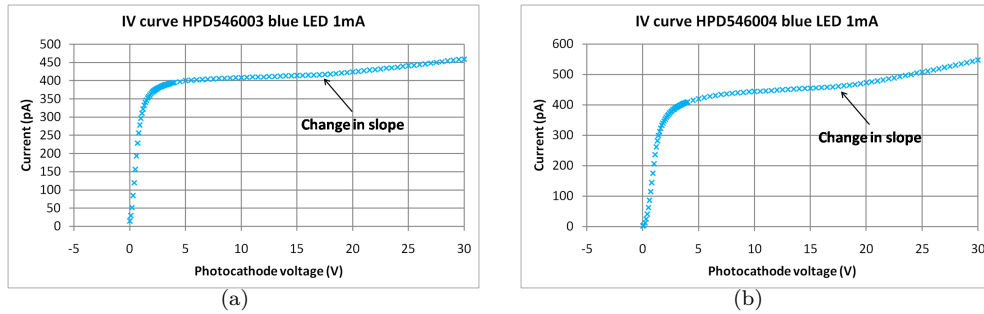


Figure 3.20. a) IV curve for the glowing H546003 illuminated by a blue LED in a zoomed version. b) IV curve for the strongly glowing H546004 illuminated by a blue LED in a zoomed version.

3.5.5 Fitting an IV curve

The IFB effect starts to have an impact on the IV curve for a glowing HPD, somewhere between 15 and 20 V. Outside this range, two separate fits can be made to the IV curve, one in the range 0 - 15 V and one in the range ≥ 20 V. The data in the range 0 - 15 V is fitted well by an inverse of V^2 , $I = a + \frac{b}{V^2+c}$, where a , b and c are constants. For voltages ≥ 20 V the IV curve of H546003 fits well to a second degree polynomial while H546004 increases faster than an exponential (Fig. 3.21).

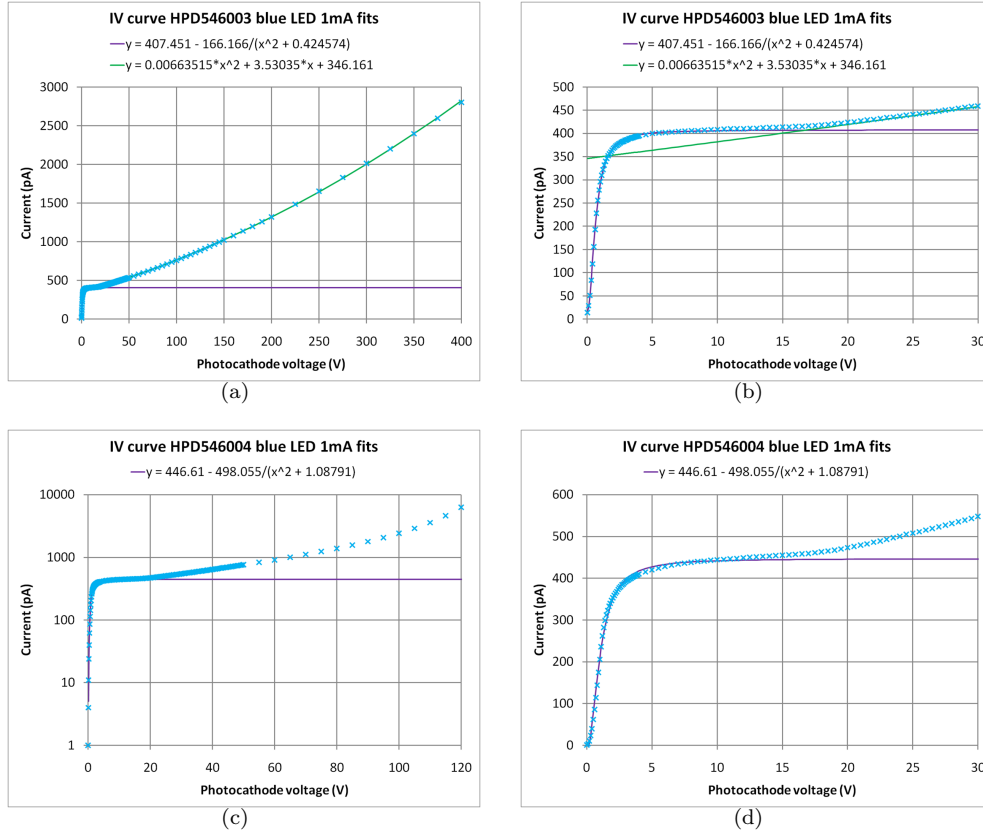


Figure 3.21. a) Fitted functions to the IV curve of the glowing H546003 in the ranges 0 - 15 V and ≥ 20 V. b) Fitted functions to the IV curve of the glowing H546003, zoomed version. c) Fitted function to the IV curve of the glowing H546004 in the range 0 - 15 V. The vertical logarithmic scale shows that the IFB effect yields an increase in current that is faster than exponential for this HPD. d) Fitted function to the IV curve of the glowing H546004, zoomed version.

3.5.6 Photocathode response limit

Comparing the glowing H546003 with the low-IFB H638005 in the low voltage range an interesting observation is made. The glowing HPD starts to detect light around 0 V applied photocathode voltage, while the low-IFB HPD detects light even with a small retarding electric field of about -0.5 V (Fig. 3.22). The blue LED has a peak wavelength of 470 nm corresponding to a photon energy of 2.64 eV and the photocathode workfunction of S20 is ~ 1.4 eV (Section 2.2.2). Assume an incoming photon with energy 2.64 eV which results in the photocathode releasing a photoelectron into the HPD body, the photoelectron is released with a maximum kinetic energy of (Eq. 2.3) $E_{max} = 1.24$ eV. This photoelectron could overcome a retarding applied voltage of up to 1.24 V, if the emission angle is right. An ideal HPD would therefore be expected to detect a current at least with a positive applied voltage of around 1.2 V or less⁵. The reason of the difference in response limit between an ideal HPD, the low-IFB HPD and the glowing HPD is unexplained.

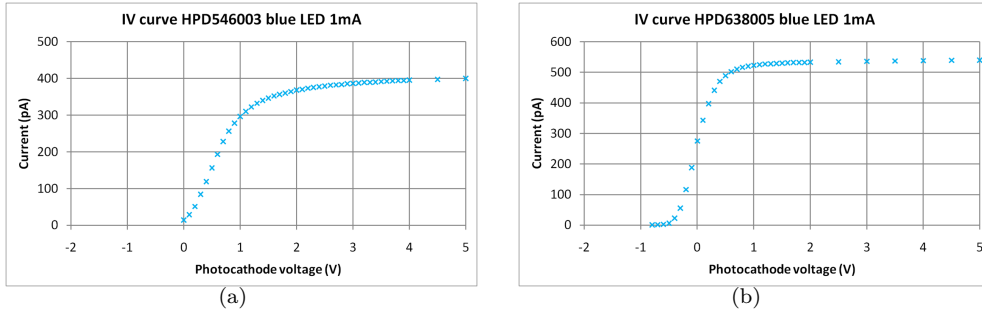


Figure 3.22. a) The glowing H546003 starts to detect a current around 0 V applied photocathode voltage. b) The low-IFB H638005 detects a current already around -0.5 V, i.e. positive voltage on the photocathode. The response is better than for the glowing HPD.

3.5.7 Comparing measurements with blue and red LEDs

All IV measurements were done with both a blue LED (peak wavelength 470 nm) and a red LED (peak wavelength 645 nm). Comparing the two obtained IV curves for each HPD after normalizing, they show a good agreement with each other (Fig. 3.23). The IFB turn-on is seen at the same voltage with a red LED as with a blue LED (Fig. 3.24). As expected with a lower energy light⁶ there is a later response from the HPDs, a higher applied photocathode voltage is required to detect the light. The difference in photon energy, $\Delta E \approx 0.7$ eV, between the peak wavelengths

⁵depending on the LED profile, which is not limited to a single wavelength, this limit should be even higher

⁶a photon wavelength of 645 nm corresponds to an energy of 1.92 eV

of the blue LED and the red LED is compatible with the observed difference in response limit, ΔV , seen in Fig. 3.25.

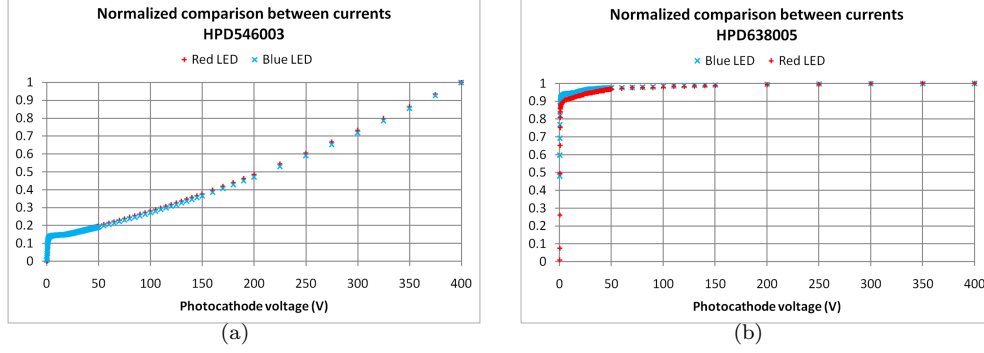


Figure 3.23. a) Normalized and overlapped IV curves for the glowing H546003 recorded with blue and red LEDs respectively, the normalization is made against the highest read current value. b) Normalized and overlapped IV curves for the low-IFB H638005 recorded with blue and red LEDs respectively.

3.5.8 Conclusions

IV measurements on the glowing HPDs show that the threshold for gas ionization inside the tubes are about 17 eV. Using a database of total ionization cross sections of atoms and molecules by electron impact, thresholds of the three main candidates are found. The ionization thresholds are displayed in Table 3.1. A threshold of 17 eV is clearly not consistent with helium.

Table 3.1. Ionization thresholds of water, helium and hydrogen [34].

Molecule	Ionization energy [eV]
H ₂ O	12.6
He	24.6
H ₂	15.4

There is a clear indication that high-IFB HPDs have a later response than low-IFB HPDs, when detecting light at low voltages. As expected the response from an HPD is seen at lower voltage for higher energy light.

3.6 Annealing with magnetic field

During operation several HPDs have been observed to show a decrease in IFB rate, this due to the IFB annealing effect (Section 3.3.3). In a lab setup where

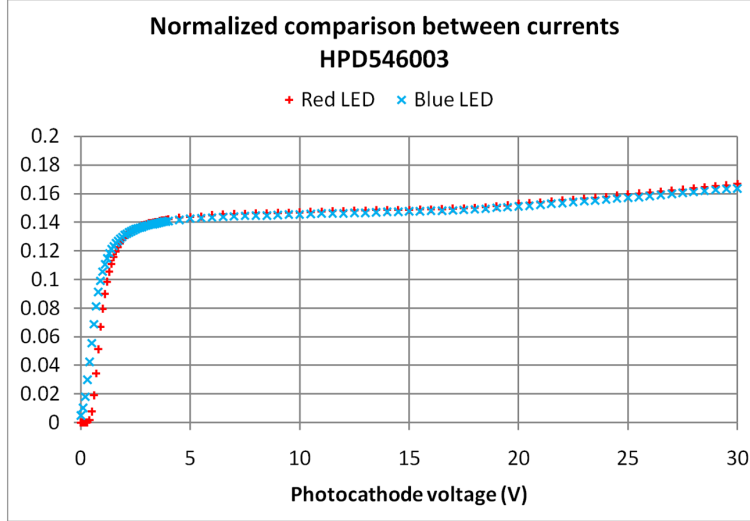


Figure 3.24. Zoom on normalized IV curves for the glowing H546003.

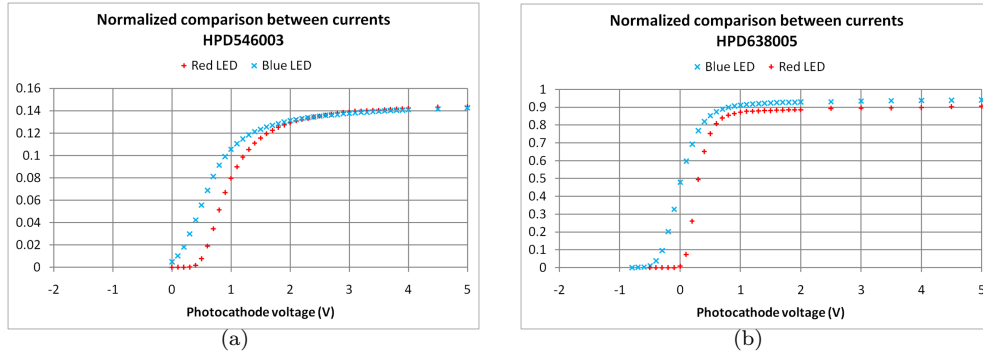


Figure 3.25. a) Zoom on the low voltage range of normalized IV curves for the glowing H546003. The difference in response limit is $\Delta V \approx 0.5$ V between the blue LED and the red LED. b) Zoom on the low voltage range of normalized IV curves for the low-IFB H638005. The difference in response limit is $\Delta V \approx 0.5$ V.

the performance of the HPD is of no importance, the annealing effect can be enhanced in different ways. Illuminating the photocathode with more light and hence increasing the number of emitted photoelectrons is one way to increase the probability of ionization and by that the annealing. However a high illumination increases the risk of damaging the HPD via IFB. Biasing the tube with a voltage where the cross section of electron-molecule interactions is high should be a way to increase the instantaneous IFB rate and hence the annealing. Theoretical values [34] give that the largest electron-impact cross section for the two main candidates, H_2O and H_2 , are at an incident electron energy in the order of 100 eV. This order of magnitude was confirmed during IV measurements on the glowing H546004, where a fast drop in readout current with time was observed when applying 130 V to the tube.

Another thought would be to try and increase the length of the electrons' trajectory inside the HPD. The number of ionized molecules should be proportional to the path length of the electrons, hence the annealing should be increased. One way to increase the path length could be by applying a magnetic field and make the electrons curl, according to the Lorentz force (Eq. 1.2). The setup would be something similar to a technique where a Penning gauge is used as a vacuum pump [35].

3.6.1 Setup

The attempt was made by introducing an axial magnetic field inside the HPD. This was done by surrounding the HPD body with a solenoid after removing the magnetic shield cylinder. The solenoid yielded a magnetic field directed almost entirely along the symmetry axis of the HPD with a maximum strength of 23 mT. The photocathode was biased with -300 V while the two electrodes and the anode were connected to ground, a simulated electric field map can be seen in the setup schematic (Fig. 3.26). A red LED was illuminating the HPD entrance window, creating a photoelectron current inside the tube body. The HPD used for these measurements was the glowing H549002. In January and February 2008 annealing tests were performed on the tube but without a magnetic field.

3.6.2 Photocurrent against magnetic field

The first measurement made was recording the photocurrent at different magnetic field strengths, the result is presented in Table 3.2. There was a maximum photocurrent for a magnetic field about 15 mT, with a factor of almost 10 increase in current compared to no magnetic field.

3.6.3 Annealing attempt

Using the results in Section 3.6.2 it was decided to put the biased HPD in a magnetic field of 15 mT for a couple of days. Data points were taken with both magnetic field on and off (when not taking data the magnetic field was always on), except for the first hour when only points with magnetic field on were taken

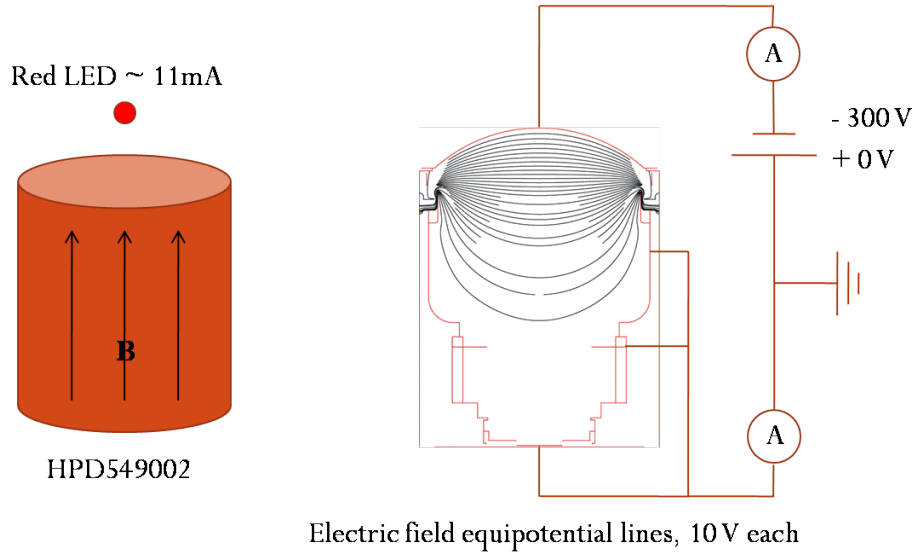


Figure 3.26. Schematic picture of the setup for the annealing with magnetic field attempt.

at a relatively high rate. The resulting plot is presented in Fig. 3.27. During the first hour there was a fast drop in current with magnetic field on. Later the currents with magnetic field on and off were slowly converging towards each other until they crossed after a couple of days. At the last data taking, current with magnetic field off was a little higher than with magnetic field on.

The full setup was switched off for 24 h and then turned on again, recording a few more data points. An increase in current, compared to before the switch off, was observed. The increase was significant enough, to be attributed to something more than variations in LED intensity only.

3.6.4 Glow light spectrum and HV ramp up after annealing

Glow light spectrum and HV ramp up scans were recorded on H549002 before, after and one month after the annealing attempt. The tube was stored in room temperature and normal atmosphere in between. Results are presented in Fig. 3.28 and Fig. 3.29.

Before the annealing with magnetic field there were clear signs of glow light during HV ramp up on the HPD, and the typical glow light spectrum was recorded. After the attempt no signs of glow light were observed neither during HV ramp up nor in the spectrum scan. One month later there were still no signs of glow light. The spectrum (Fig. 3.28 c)) looks a bit different but this is due to a change in settings of the setup, it is considered to be dark counts only.

Table 3.2. Photocurrent when applying different magnetic field strengths inside the HPD, while keeping a constant bias of -300 V on the photocathode and illuminating with a red LED. Due to rapid ion annealing with time photocurrent values are approximate.

Approximate B field strength [mT]	Electrodes/Anode photocurrent [nA]
0	255
2	306
4	275
10	441
12	790
15	2000
18	483
19	552
21	620
23	674

3.6.5 IV measurement after annealing

One month after the annealing attempt an IV scan was performed on H549002, the resulting curve is displayed in Fig. 3.30. The IV curve is clearly different from a normal curve of a glowing HPD. The IFB turn-on point around 17 V is still seen, but instead of the fast increase that usually follows this curve seems to slowly approach saturation.

3.6.6 IFB rate and photocathode response after annealing

Approximately two months after the annealing with magnetic field was started on H549002, IFB rate and radial photocathode response were measured on the HPD. At this point there was still no indication of glow light. The IFB rate was measured to be 9 %, which is a large value. The photocathode turned out to be heavily degraded (Fig. 3.31 c)).

3.6.7 Conclusions

Applying an axial magnetic field inside a glowing HPD was made as an attempt to increase the ion annealing effect. The idea was to make electrons curl and by that extend their trajectories, a longer path should lead to a greater probability of gas ionization.

The glow light in the HPD did disappear by the attempt. However not because of the desired decrease in IFB rate⁷ but by a degradation of the photocathode. With a heavy degradation in the central parts of the photocathode, the amount of secondary emission of photoelectrons from ion bombardment is low. Referring to Eq. 3.3 describing the limit for glow light to occur, there is an unwanted decrease in N_i instead of I . The damage on the photocathode, completely excludes the HPD from any further operation.

⁷the IFB rate might still had decreased though

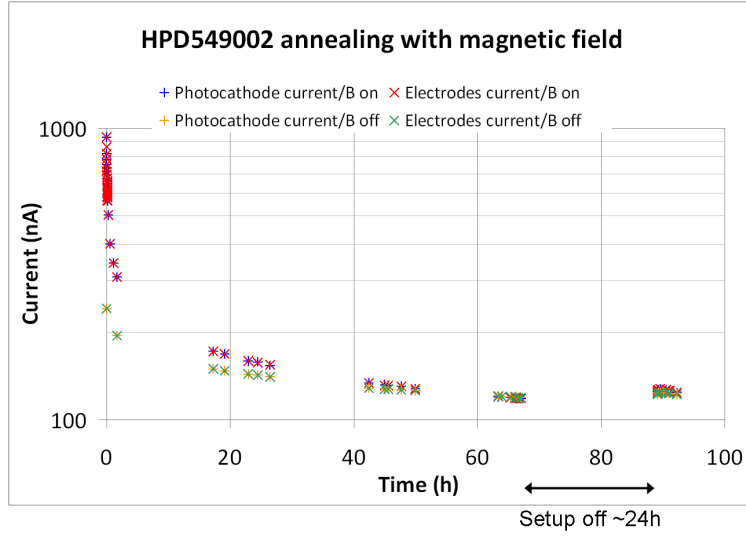


Figure 3.27. Data from the annealing attempt with magnetic field. Photocathode - and electrodes/anode currents with both magnetic field on and off are plotted against time using logarithmic current-axis.

Looking at the simplified HPD model of Ex. B.2 in Appendix it is possible to estimate the curl of photoelectrons using Eq. B.7. If $B = 15$ mT, $W_{kin} = 1$ eV and $\varphi = \frac{\pi}{6}$ rad the photoelectron helix trajectory will have a radius $r \approx 0.1$ mm which is small. A small-radius curl has been confirmed by simulations on photoelectron trajectories inside an HPD using the true electric field configuration and an axial magnetic field. Hence the observed rise in current when applying a magnetic field (Section 3.6.2) is not likely to be explained by photoelectrons curling. Since the radius in Eq. B.7 is proportional to $\sqrt{m}$, it is more likely that the rise is caused by ions curling and striking the photocathode further out from the center where it is less degraded. This would also explain why the photocathode is more degraded after the annealing with magnetic field.

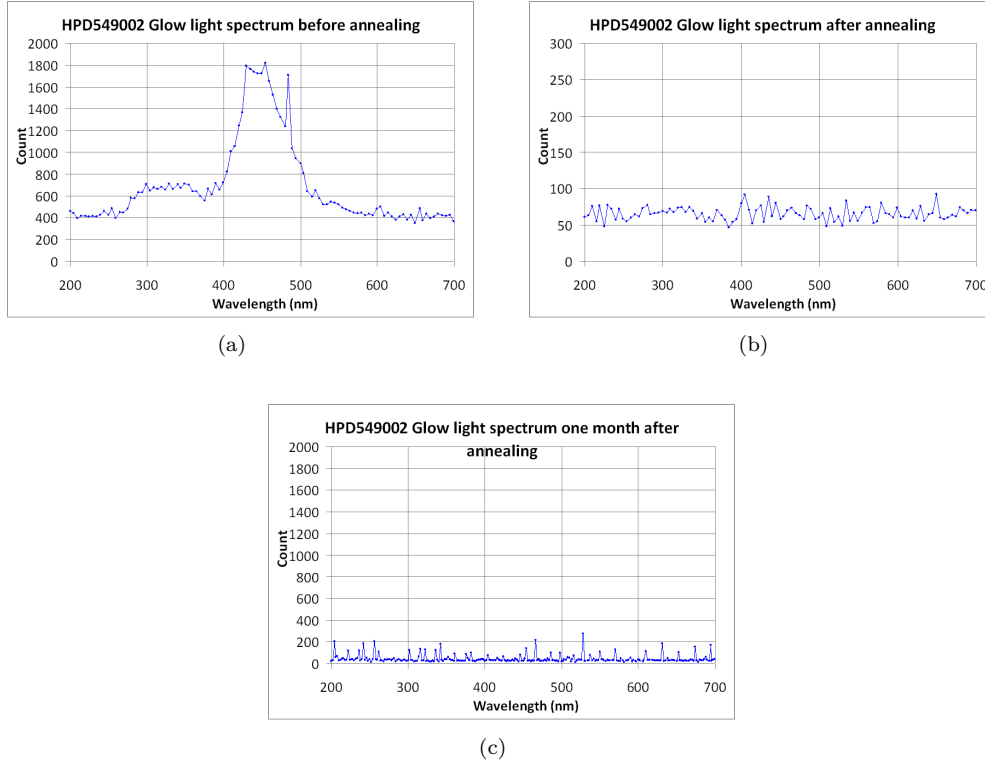


Figure 3.28. a) Glow light spectrum recorded on H549002, before the annealing with magnetic field. Photocathode biased with -16 kV, 60 s integration time and 5 nm steps. b) Glow light spectrum recorded on H549002, after the annealing with magnetic field. Photocathode biased with -16 kV, 10 s integration time and 5 nm steps. c) Glow light spectrum recorded on H549002, one month after the annealing with magnetic field. Photocathode biased with -16 kV, 60 s integration time and 2 nm steps. There was a change in settings during this measurement, however the spectrum is considered to be dark counts only.

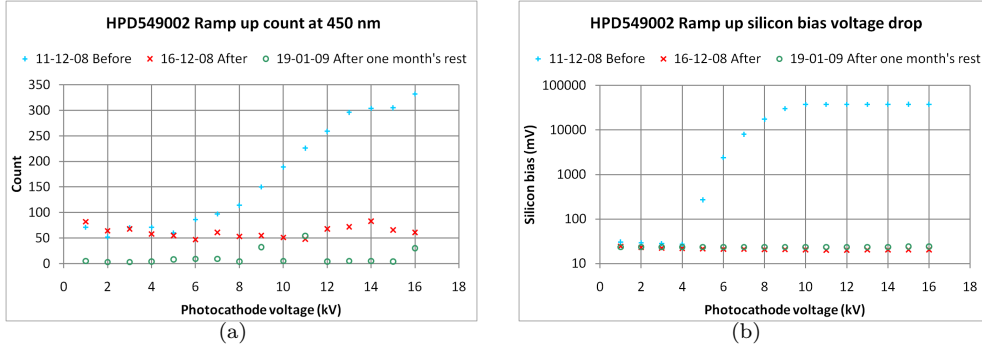


Figure 3.29. HV ramp up performed on H549002. a) Photon count at 450 nm as a function of applied HV in three datasets: Before, after and one month after the annealing with magnetic field. b) Voltage drop over the silicon anode as a function of applied HV in three datasets: Before, after and one month after the annealing with magnetic field.

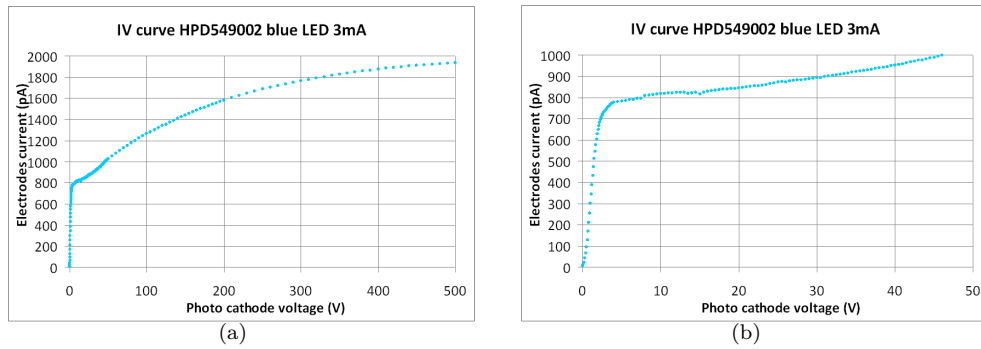


Figure 3.30. a) IV curve for H549002 illuminated by a blue LED, recorded one month after the annealing with magnetic field. b) The same IV curve in a zoomed version.

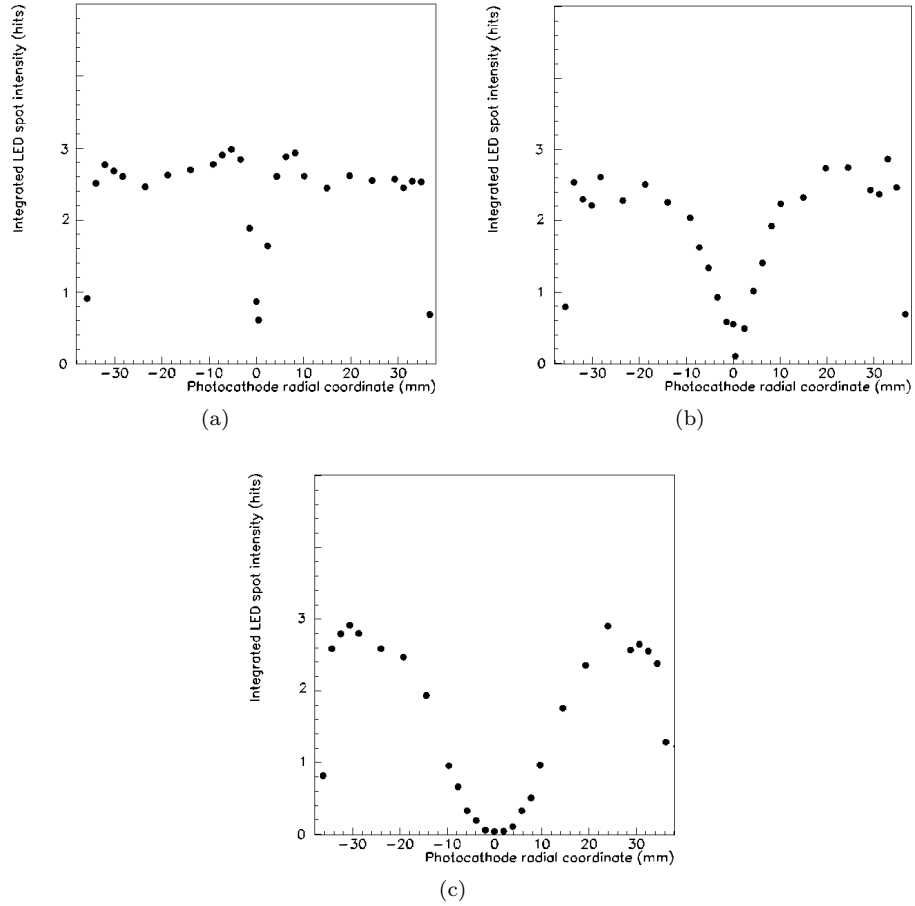


Figure 3.31. a) Integrated radial photocathode response of H549002, recorded in January 2008 shortly after the tube was removed from RICH 2 due to glow light [30]. b) Integrated radial photocathode response of H549002, recorded in February 2008 after first annealing tests (without magnetic field). c) Integrated radial photocathode response of H549002, recorded in February 2009 after annealing with magnetic field.

Chapter 4

HPD image stability

4.1 Introduction

Drift effects of the HPD photocathode image have been first identified in summer 2009, during test campaigns of the Magnetic Distortion Measurement System (MDMS) in the RICH 1 detector. It was observed that a fraction of HPDs showed a shift of their photocathode image between two different data-taking runs well separated in time. The center coordinates of the photocathode image are calculated from raw data in which the HPDs are illuminated with an LED pattern. Since the HPDs are firmly fixed to a mechanically stable structure (Section 1.6), this unexpected drift phenomenon cannot originate from HPD motions per se. This effect was further confirmed some weeks later in RICH 2, when the photocathode images for some HPDs were seen to shift position during a long run, illuminating the detector with a continuous LED. The magnitudes of some shifts were significantly larger than the LHCb pixel uncertainty. A shift in HPD image position, if not corrected for, affects the physics performance of the detector, consequently an extensive investigation of the phenomenon was started.

4.1.1 Pixel uncertainty

The impact coordinate of a single photoelectron hitting a pixel in the segmented silicon anode is in one dimension, the x -dimension, modeled as a uniform distribution with probability density function [14]

$$f(x) = \begin{cases} 1 & 0 \leq x \leq 1 \\ 0 & \text{otherwise} \end{cases} \quad (4.1)$$

when $x \in [0, 1]$. The standard deviation of the distribution is $\sigma_x = \frac{1}{\sqrt{12}}$. Reading out data from single photoelectron hits in an HPD pixel chip using standard PHYSICS (LHCb) mode (Section 2.2.3) therefore has the uncertainties of $\sigma_x = \frac{1}{\sqrt{12}}l_x$ and $\sigma_y = \frac{1}{\sqrt{12}}l_y$ where $l_x \times l_y = 500 \times 500 \mu\text{m}^2$ is the pixel size.

4.2 Image drift analysis

The image drift analysis is made on the chip plane rather than the photocathode plane and therefore it is appropriate to speak in terms of pixels instead of a length unit when measuring the magnitude of a movement. Since the pixel uncertainty is $\frac{1}{\sqrt{12}} \approx 0.29$ pixels (Section 4.1.1) an observed movement with an RMS value larger than 0.3 LHCb pixels is defined to be a significant movement. The RMS value is a statistical measure of the magnitude of a varying quantity.

Definition 4.1 *The Root Mean Square (RMS) of a set of n values $\{x_1, x_2, \dots, x_n\}$ is given by*

$$\text{RMS}_x = \sqrt{\frac{x_1^2 + x_2^2 + \dots + x_n^2}{n}}. \quad (4.2)$$

4.2.1 Method

When analyzing the photocathode image shift the problematic thing is essentially to put a correct cut for each individual HPD of what is considered to belong to the photocathode and not. The cut is a positive integer value, all HPD pixels that detect at least the same amount of photon hits as the cut value are put to 1, while the other pixels are put to 0 (this procedure is visually displayed in Fig. 4.3). Background noise (mainly due to backscattering), IFB rate and illumination level vary from HPD to HPD and a specific cut for one HPD may not be an appropriate cut for another (Fig. 4.1). HPDs with too much background noise, too high IFB rate or too low illumination level have to be excluded from the analysis. Another problem can be the HPD chip register settings (Section 2.2.3) which are not always optimal. These settings can be adjusted but that requires an intervention from experts and is only carried out occasionally.

When analyzing a run from one of the RICH detectors, the first step is to split the data into time slices. Afterwards individual cuts, of number of photoelectron hits in a pixel, are applied for each HPD to find the photocathode images (Fig. 4.2). The cut for an image is the same in all time slices.

The center coordinates and radius of each HPD image in each time slice are found by a simple fit of a ring to the cut photocathode image. The center coordinates are first calculated by taking the center of gravity of all pixels in the image. Assuming the photocathode is a circular disc, the radius is calculated by stepping in several directions from the center to the edge and taking the average distance (Fig. 4.3).

The calculation of center x - or y -coordinate is an average over 32 pixel rows or columns (in PHYSICS mode). Assume that the calculation of center x -coordinate (y -coordinate) in one row (column) has the uncertainty σ and that the calculation in one row (column) is independent from the calculations in the other rows (columns). The uncertainty of the average over 32 rows (columns) is then $\frac{\sigma}{\sqrt{32}}$ [8]. This fact combined with the binary cut of the photocathode image, implies that the uncertainties are small when calculating center coordinates. The same argumentation can be made for the radius calculation. Plots of center coordinates

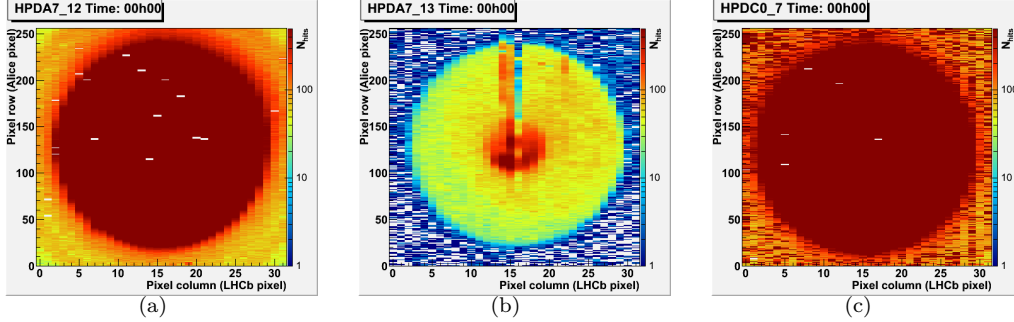


Figure 4.1. Illustration of why individual cuts are necessary for each HPD when finding the photocathode image. Hitmaps are from different HPDs but in the same run. a) Hitmap of a high-IFB HPD where a relatively high cut has to be applied. Some dead pixels can be noticed. b) Hitmap of a low illuminated HPD where a relatively low cut has to be applied. The unusual middle column pattern is attributed to sub-optimal chip register settings. c) Hitmap of a very-high-IFB HPD. This HPD has to be excluded from the analysis.

are presented without error bars due to the problem of estimating the uncertainty in one row (column).

The calculated image center coordinates and radius are plotted against time and the RMS values of the deviation from the mean¹ for each property in each HPD are calculated (Fig. 4.4). The motion amplitude is expressed by the quantity $RMS_C = \sqrt{RMS_x^2 + RMS_y^2}$ and the change in radius by RMS_R .

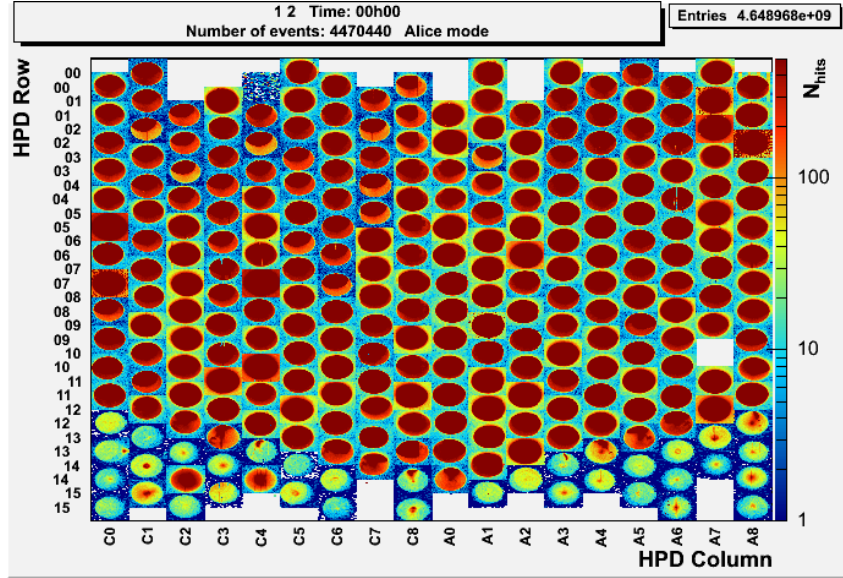
The method has been observed to be reliable, as long as the photocathode cuts are well chosen, by comparing to animated single HPD hitmaps from raw data. It is somewhat more sensitive for the radius calculation than the center coordinates calculation. Factors that can affect the results are: Dead and noisy pixels in the chip, shadowing from the HPD magnetic shield, discharges, high backscattering.

4.2.2 Results in RICH 2

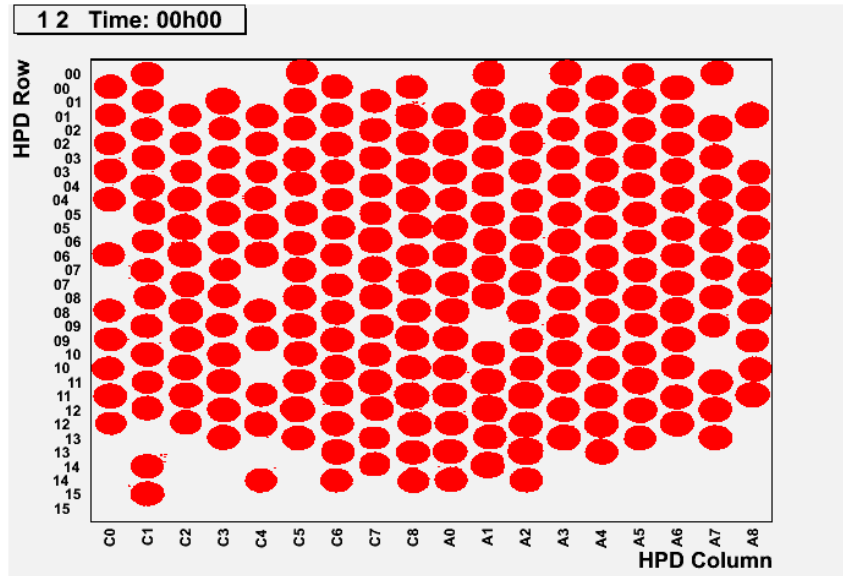
Around 10 different RICH 2 runs have been analyzed for image drifting including continuous laser runs, beamer pattern runs and dark count runs. The runs are from a widespread time period between June 2008 and September 2009. Most of the runs were taken before the image drifting phenomenon in the HPDs was known and are hence made for other studies, they are in the order of 20 h long. Later runs were dedicated to the study of image drifting and are longer, up to 90 h.

It should be noticed that it can be misleading to compare results coming from different runs, especially the magnitude of motion observed. Depending on duration of the run, trigger rate and illumination level, the amount of statistics vary

¹i.e. the standard deviation



(a)



(b)

Figure 4.2. a) Hitmap from a laser run in RICH 2 in August 2009. The run was 62.4 h long and in the analysis it was divided into 50 time slices. The figure displays the first slice. b) Hitmap of the photocathode images from the same time slice, found by applying individual cuts to each HPD. Some HPDs have been removed from the analysis due to high noise level, high IFB rate or too low illumination.

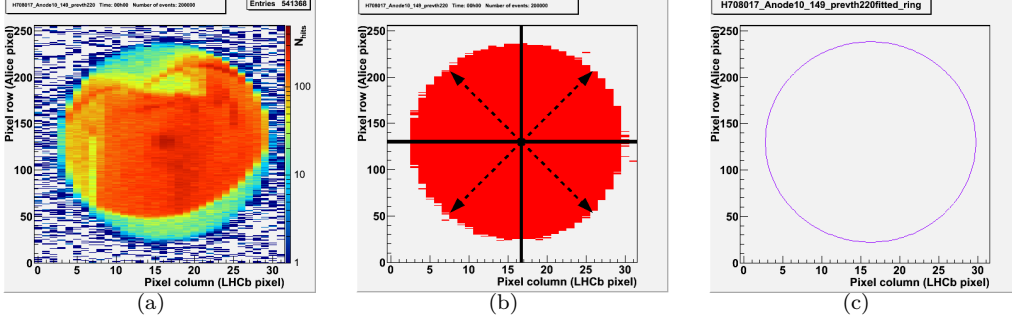


Figure 4.3. Procedure when calculating the HPD photocathode image center coordinates and radius. a) Raw hitmap of an HPD. b) Cut hitmap of the same HPD with an illustration of center coordinates - and radius calculation. c) Resulting ring fitted to the image.

from run to run.

The largest magnitude of image motion calculated in a RICH2 HPD had $\text{RMS}_C \approx 1$ LHCb pixel and an absolute change in center position $\sqrt{(\Delta x)^2 + (\Delta y)^2} \approx 3.5$ LHCb pixels (Fig. 4.5). No observed shift rate has been seen faster than 1 pixel/hour. Shifts in an HPD are unpredictable and show no periodic behavior over a time scale up to 90 h, it is rather observed as a random effect. Although there is no clear correlation between different runs in the respect of which HPDs show the effect, it is clear that some specific HPDs are more likely to shift than others. About ten tubes in RICH2 have been listed as HPDs which regularly show a significant effect. In general about 5 - 25 % of HPDs in a run show a significant motion, the number varies from run to run. The change in HPD image radius is not as evident but is clearly seen in some HPDs. Results from a typical laser run are presented in Fig. 4.6. Examples of typical shifts are presented in Appendix Section C.2.

Some correlation plots are displayed in Fig. 4.7. No obvious correlations can be established but as mentioned there are HPDs showing significant image drift in more than one run. Attempts to correlate the image drift with environmental variables, such as temperature and pressure, have been made but without success. No correlation with HPD IFB rate has been seen either.

4.2.3 Results in RICH1

RICH1 data has been analyzed for HPD image drifting similarly to RICH2 by the MDMS team during magnetic distortion calibration measurements. The used method is independent from the RICH2 method and different in the sense that HPD image discs are fitted by elliptical curves. Results are consistent with RICH2 results and confirm the effect.

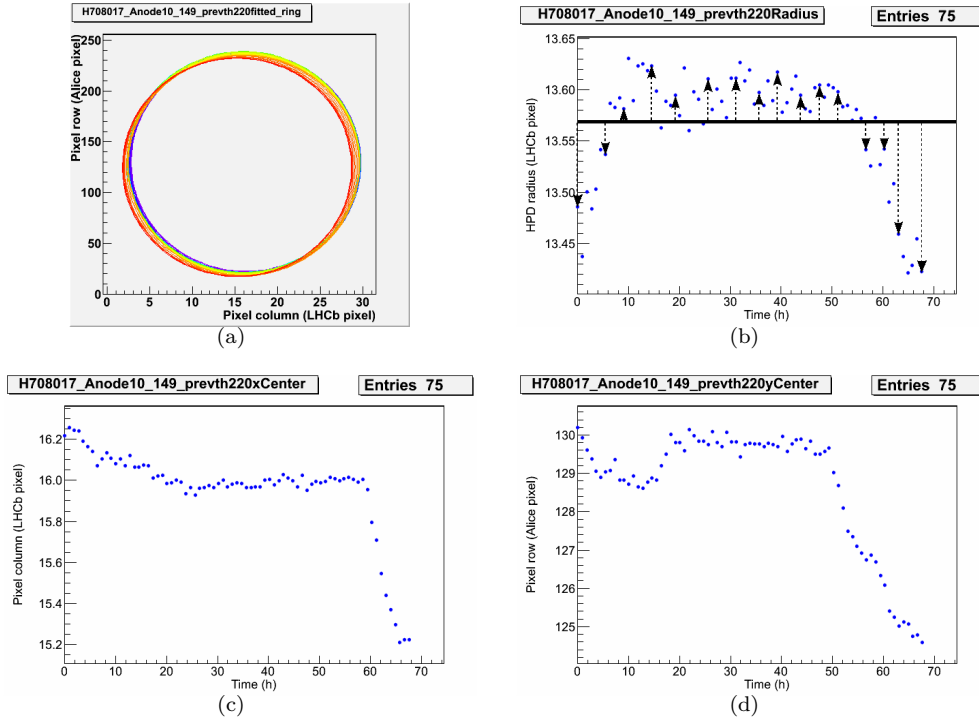


Figure 4.4. a) Illustration of an HPD image shift in a run of 68.5 h divided into 75 time slices. The fitted rings for each time slice are displayed by the violet - to red spectrum where violet corresponds to $t = 0$ h and red to $t = 68.5$ h. b) Calculated radius against time in the same run with an illustration of how the RMS value is found. c) Calculated center x -coordinate against time in the same run. d) Calculated center y -coordinate against time in the same run.

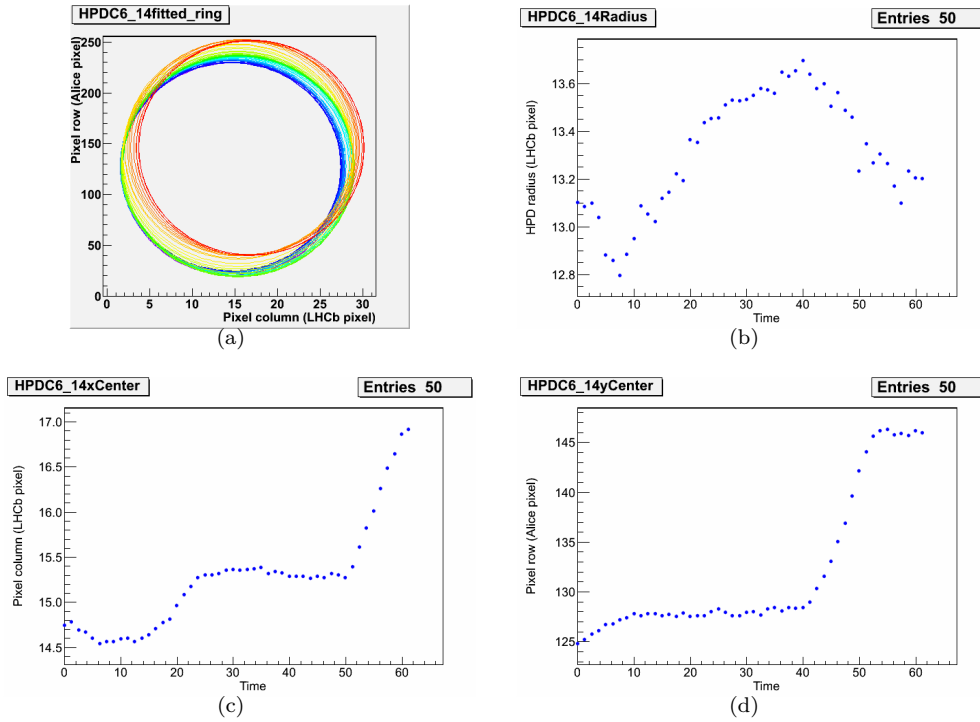


Figure 4.5. a) HPD image shift in C6_14 in a 62.4 h long laser run recorded in August 2009 (RICH 2). This HPD showed the largest magnitude of motion calculated in any run. b) Calculated radius against time. c) Calculated center x -coordinate against time. d) Calculated center y -coordinate against time.

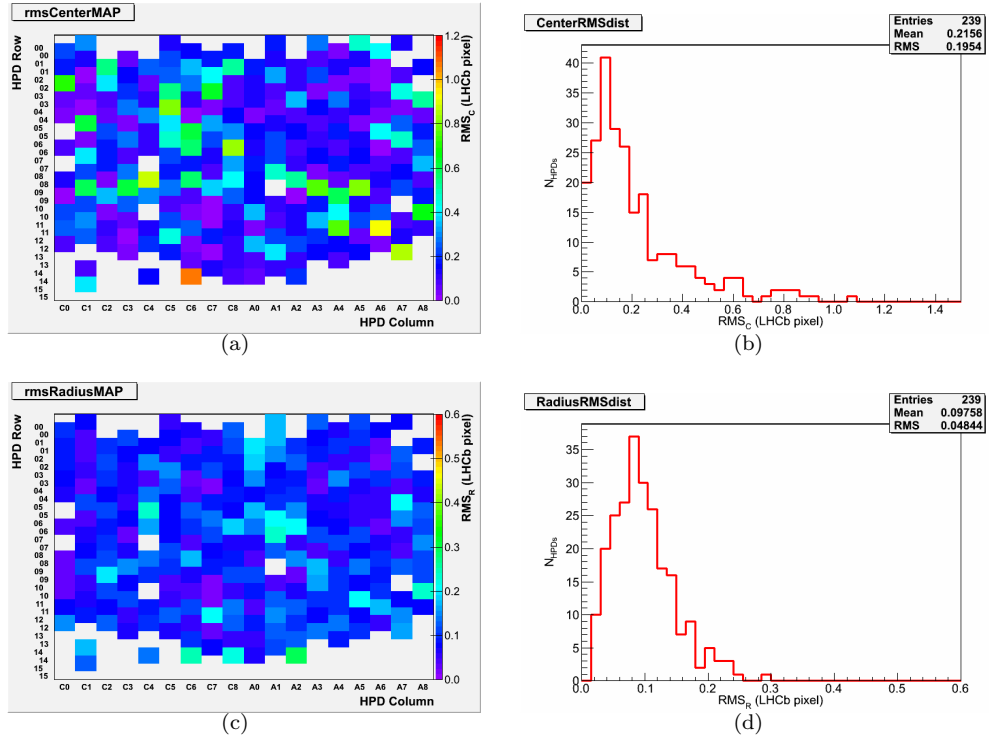


Figure 4.6. a) HPD map of RMS_C values in a 62.4 h long laser run recorded in August 2009 (RICH 2). White color means that the HPD was excluded from the analysis. b) Distribution of RMS_C values from the same run. c) HPD map of RMS_R values from the same run. d) Distribution of RMS_R values from the same run.

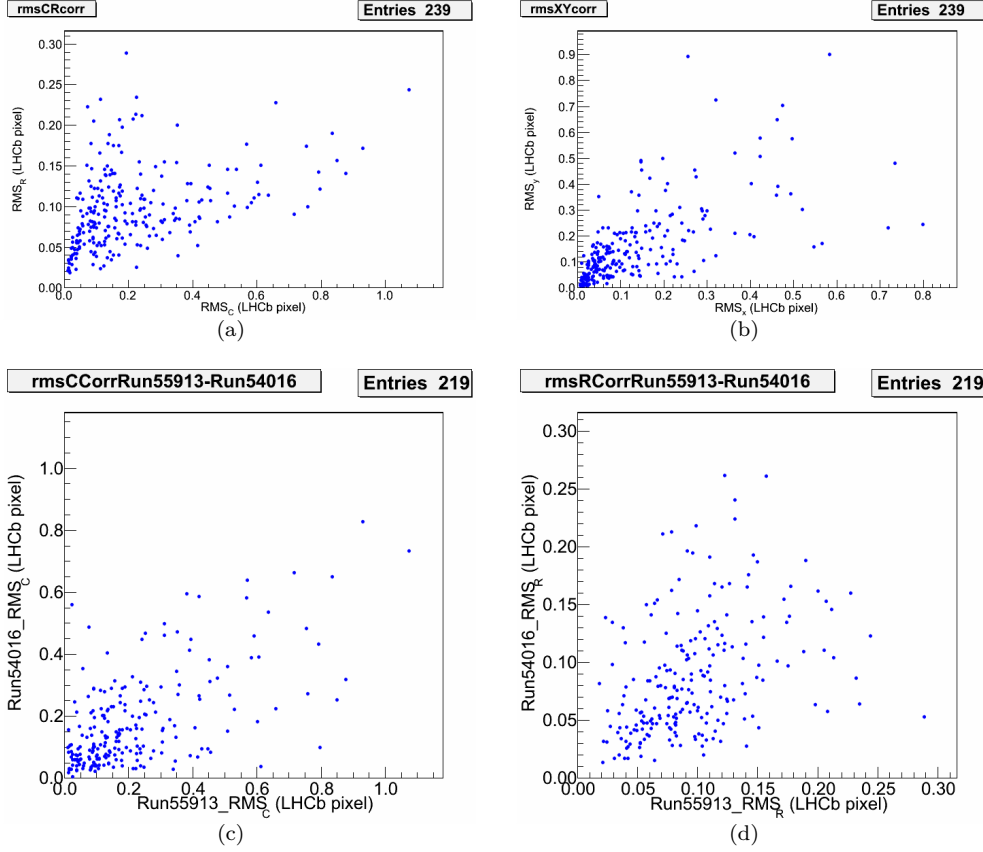


Figure 4.7. a) Correlation between RMS_C values and RMS_R values in a 62.4 h long laser run recorded in August 2009 (RICH 2). b) Correlation between RMS_x values and RMS_y values in the same run. c) Correlation between RMS_C values from two different laser runs, both approximately 60 h long. d) Correlation between RMS_R values from the same two runs.

4.2.4 Analysis in laboratory environment

In October 2009 an HPD intervention was made in RICH 2 to replace high-IFB HPDs in the risk zone of entering the glowing regime. During this intervention one HPD, H708017 (position A7_13), was removed for dedicated image drifting studies in laboratory environment. H708017 was one of the HPDs regularly showing significant image drift in RICH 2 runs. It had a measured IFB rate $\sim 1\%$ at the time of the removal and was not a risk HPD in the respect of glow light.

There are advantages of doing HPD studies on one single HPD in a controlled laboratory environment over on-detector investigations in the RICH detectors. Since data is read from one HPD only, instead of 288 HPDs (RICH 2), it is possible to increase the statistics in the HPD and extend the time of the investigation. Illumination properties, such as shape, intensity and light energy, are easy to control by using LEDs. Discriminator threshold in the pixel chip (Section 2.2.3) can be adjusted and LV - HV distribution can be modified. By confirming the effect in the laboratory environment it is also possible to exclude any problem in the overall system aspect (e.g. hardware, infrastructure, readout software) of the RICH detectors.

Lab setup

A schematic of the lab setup is displayed in Fig. 4.8. Two red LEDs were used to illuminate the HPD, a widespread LED and a pencil LED. The pencil LED gives a light concentrated to a small area and with a strong intensity compared to the widespread LED. The tube was biased with 18 kV using the same high voltage supply system as in the RICH detectors. The grounding scheme was as similar as possible to the detectors with LV and HV grounds merged on holding mechanics. In some runs an extra ground cable, not used inside the detectors, was connected to the HPD to see if any effects could be observed. The discriminator threshold of the chip was set to ~ 1150 e. Runs were typically performed by sampling bursts of 20 000 events, separated with a constant time interval of 5 - 15 minutes in between.

Method

Two independent methods have been used to analyze the drift in photocathode image. The first method is the same as used in the RICH 2 detector. The second method is dedicated to analyze the shift of the concentrated light spot, yielded by the pencil LED. In each time slice the spot is fitted by a 2-dimensional Gaussian [36] after subtracting the background (generated by the widespread LED and other background sources such as dark counts). The peak position of the light spot is plotted against time, similarly to the x - and y -coordinates of the photocathode image center calculated in the other method.

Results

The image drift in tube H708017 was initially confirmed in two different runs of 1000 bursts taken with 5 min time intervals, using the widespread LED only. The

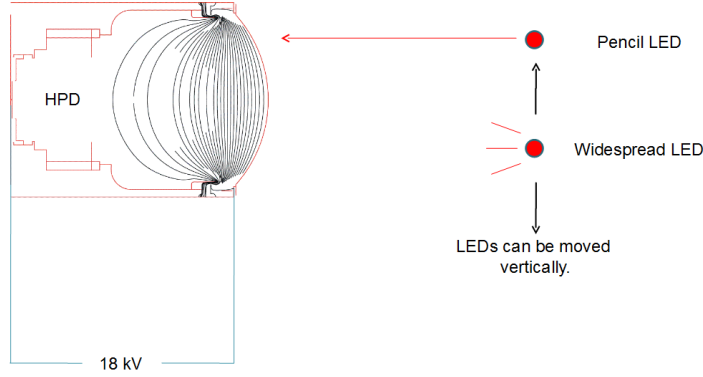


Figure 4.8. HPD image drift analysis setup.

first run of ~ 90 h was made with the LED in a central position illuminating the full photocathode, while the second run of ~ 93 h² was made with the LED in an edge position generating a shadowing effect from the magnetic shield cylinder. Results from the first run are displayed in Fig. 4.9 and gave $\text{RMS}_x = 0.22$ LHCb pixels and $\text{RMS}_y = 2.18$ ALICE pixels³. They are similar to what was observed while the tube was still inside RICH 2. Still no periodicity is seen in the movement.

The pencil LED was introduced to illuminate the edge of the HPD entrance window. Two different positions have been used in four different runs, two runs with upper middle part illumination and two with lower middle part illumination. The widespread LED overlapped the pencil LED as a background illumination on the window. Runs were started right after the pencil LED was moved to its position or right after HV ramp up was performed. This means that the beginning of the runs were influenced by a recent change in illumination profile, made intentionally to observe possible effects. Similarly, the light profile was intentionally made to be non-uniform. In the RICH detectors, the light profiles are much more uniform.

All four runs with the pencil LED further confirmed the image drifting effect by showing significant image shifts, other important results were also found. The light spot from the pencil LED was shifting in a way well-correlated to the HPD image center shift. This should rule out any potential drift in discriminator threshold within the pixel chip, as being responsible for the image drifting effect. The

²the duration of a run is depending on the computer CPU used at the moment, therefore two different runs made with the same conditions are not necessarily equally long

³which yield $\text{RMS}_C = \sqrt{\text{RMS}_x^2 + (\text{RMS}_y/8)^2} = 0.35$ LHCb pixels

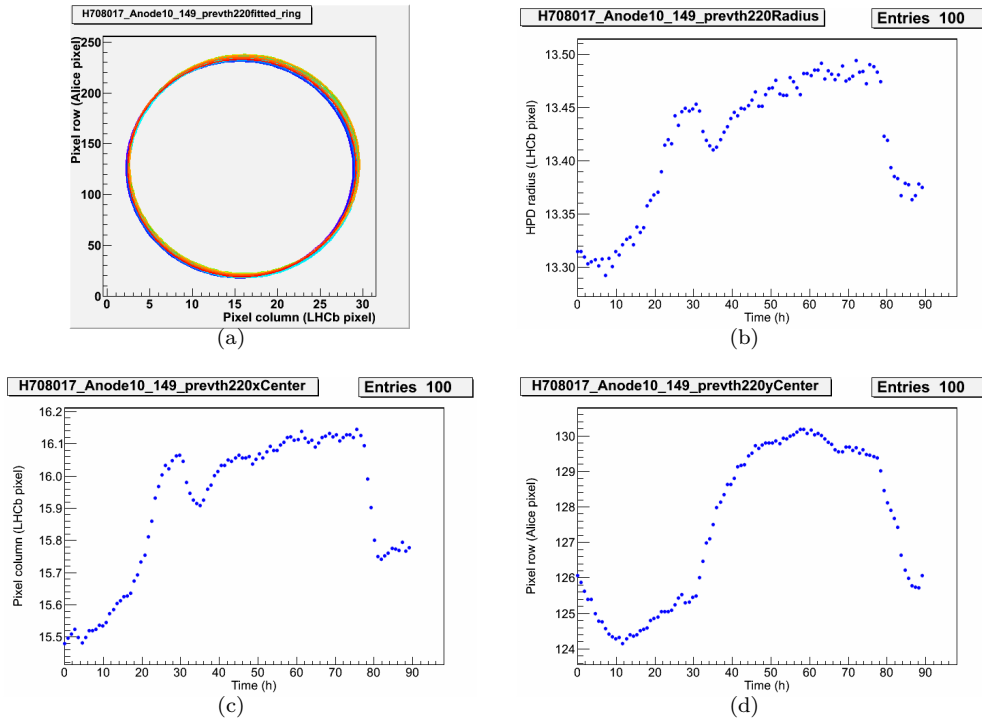


Figure 4.9. a) HPD image shift in H708017 in a 90 h long run with widespread LED recorded in October 2009. 1000 bursts of 20 000 events have been merged into groups of 10, making 100 time slices. b) Calculated radius against time. c) Calculated center x -coordinate against time. d) Calculated center y -coordinate against time.

intensity of the light spot is too strong. Furthermore the HPD image was seen to shift relatively rapidly towards the position of the light spot in the beginning of the runs. This could be interpreted as there being a correlation between illumination profile and shift direction. The center position plots of some of the runs showed possible signs of charging - and discharging effects inside the HPD. Connection of an extra ground cable to the HPD did not take away the drifting effect, a small reduction in magnitude of motion was observed but not significant enough to draw any conclusions.

Results from the runs with pencil LED are collected in Table 4.1 and some plots are displayed in Fig. 4.10 and in Appendix Section C.2. IFB rate and two-to-one cluster ratio⁴ are included as extra information.

Table 4.1. Results from runs with both a pencil LED and a widespread LED.

Run	RMS _x [LHCb pixels]	RMS _y [ALICE pixels]	RMS _R [LHCb pixels]
Pencil up	0.202	1.472	0.045
Pencil down	0.209	1.074	0.046
Pencil down, extra GND	0.183	1.304	0.037
Pencil up, extra GND	0.137	1.074	0.042

Measurements on another HPD

In June 2009, right after the HPD image drifting effect was identified in RICH 1, measurements were performed on another LHCb production HPD in the laboratory environment. This was done using only the pencil LED and the method of fitting a 2-dimensional Gaussian to the light spot after subtracting the background. These measurements showed no indication of image drift in the HPD and were therefore soon abandoned. The same conclusion was drawn in the year 2005 after long-term studies of a pre-series HPD. The image stability monitored over one month was then seen to be fully satisfactory. This is interpreted as a further confirmation of the image drifting effect being stronger in some HPDs than others.

4.3 Conclusions

HPD image drift has been confirmed both on-detector and in laboratory environment, by several measurements using different independent methods. Largest absolute shift measured in a run is around 3.5 LHCb pixels with RMS_C $\approx$ 1 LHCb pixel. Since the 1-dimensional pixel uncertainty is 0.29 LHCb pixels, when running the detector in PHYSICS mode, the effect has to be corrected for. The most rapid shift observed is in the order of 1 LHCb pixel/hour which means that it is a relatively slow effect. A regular (< 1 hour) calibration of HPD positions should be sufficient in the RICH detectors.

⁴ $\frac{N_2}{N_1+N_2}$ is a useful property for estimating the amount of charge sharing in the pixel chip

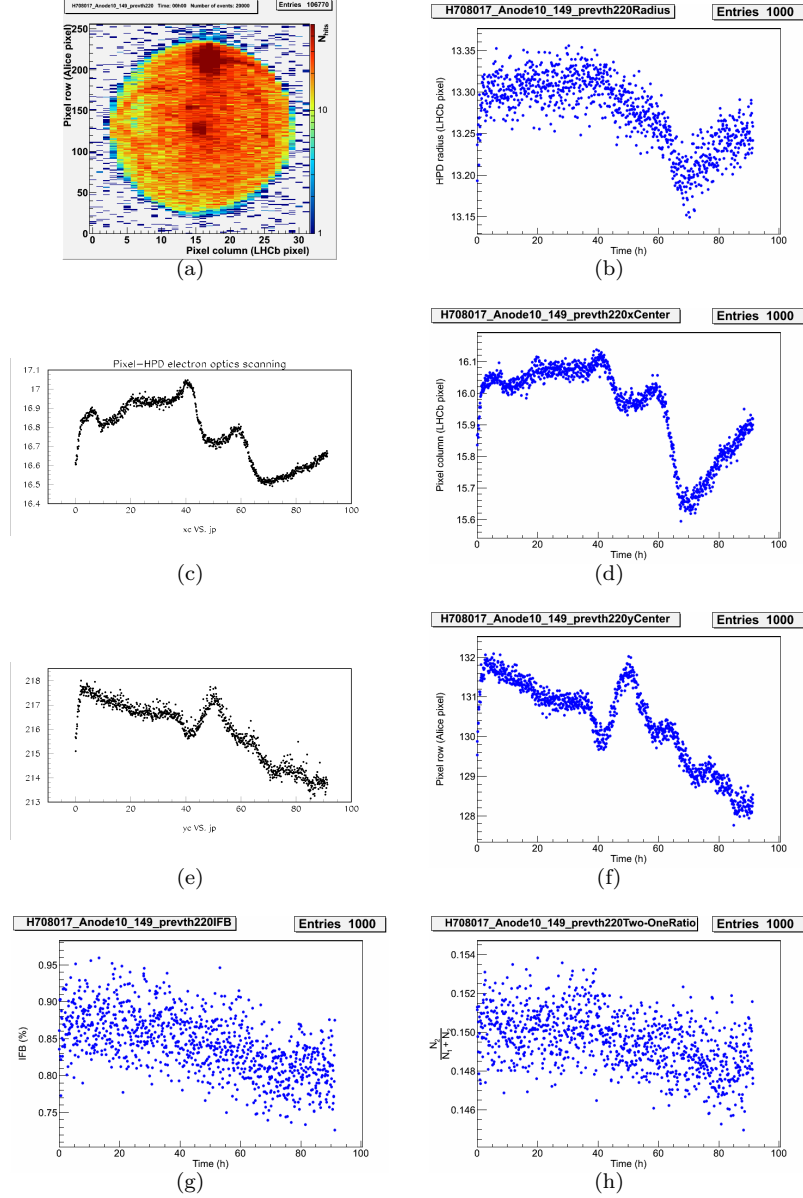


Figure 4.10. Plots from a 91.5 h long run in November 2009 with H708017, using a pencil LED and a widespread LED. An extra ground cable was connected to the HPD. 1000 bursts of 20 000 events were analyzed as 1000 time slices. a) Hitmap showing that the position of the pencil LED was set to illuminate the upper middle part of the HPD window. b) Calculated radius against time. c) Calculated pencil position x -coordinate against time. d) Calculated center x -coordinate against time. e) Calculated pencil position y -coordinate against time. f) Calculated center y -coordinate against time. g) IFB rate against time. h) Two-to-one cluster ratio against time.

A strong light spot is seen to shift together with the HPD image. This should exclude any drift of discriminator threshold within the pixel chip as being the cause of the effect. Furthermore there are signs indicating that the image shift is connected to illumination profile. There are also possible signs of charging - and discharging effects inside the HPD. Measurements clearly show that the image drifting effect is stronger in some HPDs than others. No periodicity or correlation to environmental variables has been observed in the motion, it is rather observed as a random effect.

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Appendices

Appendix A

Introduction to semiconductor physics

A.1 Semiconductors

A semiconductor is a solid with an electrical resistivity between that of a conductor and an insulator. In the energy band model a conductor has numerous free electrons in the conduction band which overlaps with the valence band, while semiconductors and insulators have nearly empty conduction bands and nearly full valence bands. Valence electrons can however be excited to the conduction band and the amount of energy required for this to happen is what separates a semiconductor from an insulator (Fig. A.1).

Electrons are fermions and are described by Fermi-Dirac statistics. They follow the Pauli exclusion principle, which states that two electrons in a system may not occupy the same quantum state simultaneously [37]. The Fermi-Dirac distribution is given by the formula

$$P(E) = \frac{1}{1 + \exp\left(\frac{(E-E_F)}{\kappa T}\right)} \quad (\text{A.1})$$

where $P(E)$ is the probability that a state, at an energy E , is occupied by an electron. κ is the Boltzmann constant and T the temperature of the system. The Fermi level, E_F , is defined as the energy where the chance of a state being occupied by an electron is one half. At absolute zero ($T = 0$ K) all states with an energy below the Fermi level are occupied while all states with a higher energy are empty. In the energy band model for semiconductors the Fermi level is put relative to the energy level of the bottom of the conduction band, E_C , and the top of the valence band, E_V . In a system of thermal equilibrium the position of the Fermi level determines both the density of electrons and the density of holes, and it can be situated in a band gap (forbidden zone) even though there are no states at that particular energy.

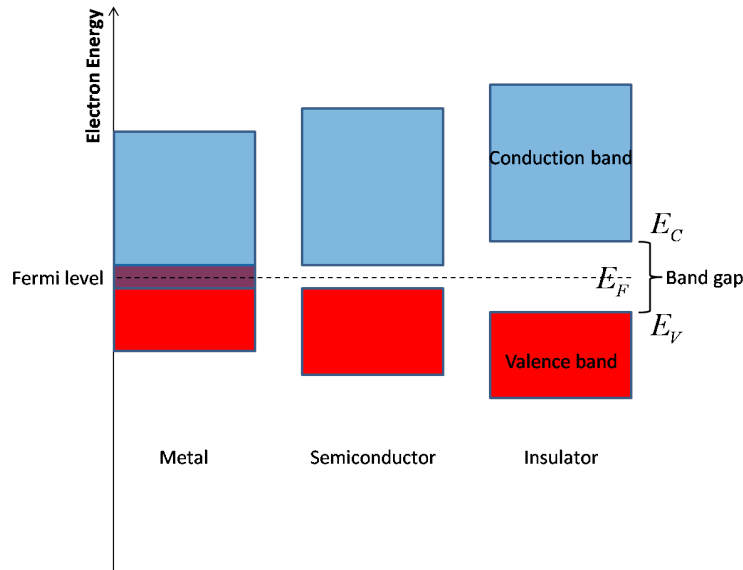


Figure A.1. The electron energy band model in solid state physics describes the ranges of energy that an electron in a solid is allowed and forbidden to have.

A.1.1 Doping

Most semiconductors have the same crystal structure as diamond. By introducing small quantities of chemical impurity into the crystal lattice the electrical properties of the semiconductor can be changed. This process is called doping and the added impurity element is the dopant [37]. There are two kinds of dopant, donors and acceptors. Donor atoms have more valence electrons than the original semiconductor and using a donor results in loosely bounded electrons that are relatively free to move in the lattice. In other words the donor atoms introduce states below but close to the conduction band, electrons at these states can easily be excited to the conduction band. The obtained material is a n-type semiconductor. A p-type semiconductor is obtained in the same way but using an acceptor, that is an atom with less valence electrons, to introduce absence of electrons (holes) into the lattice. A n-type semiconductor has its Fermi level closer to the conduction band while the Fermi level of a p-type semiconductor is closer to the valence band.

A.1.2 Carrier generation and recombination

Processes where mobile charge carriers (electrons and holes) are created and eliminated in a semiconductor are called carrier generation and carrier recombination, these processes are fundamental for the operation of many semiconductor devices. Carrier generation is a process where an electron gain energy to move from the valence band to the conduction band. This results in two mobile charge carriers, the free electron and the electron-hole. Recombination is the opposite, when an

excited electron in the conduction band loses energy and re-occupies an energy-state of an electron-hole in the valence band. Generation and recombination is a result from electrons interacting with other carriers in the lattice of the material or with photons.

A.1.3 p-n junction

By joining a p-type and n-type semiconductor together in close contact a p-n junction is created (Fig. A.2) with properties making it the basis in many electronic devices [37]. A n-type semiconductor has an excess of free electrons while a p-type semiconductor has an excess of holes, when two of them are put together electrons will diffuse from the n-type into the p-type leaving positive donor ions behind in the n-type. Likewise holes will diffuse from the p-type into the n-type with negative acceptor ions left behind. After the transfer the electrons are eliminated by recombination with holes in the p-type and the holes are eliminated by recombination in the n-type. This results in charged ions being left behind adjacent to the interface of a region which is depleted of mobile charge carriers. This region is usually referred to as the depletion layer. This layer is nonconducting because of the created electric field which opposes further exchange of charge carriers.

Applying an external bias over a p-n junction creates a difference in Fermi levels between the p-side and the n-side. Reverse bias is when applying a more negative voltage to the p-side than the n-side of the junction, while forward bias is the opposite. Under reverse bias the barrier potential increases and the depletion layer becomes wider. Contrary forward bias decreases the barrier potential and narrows the depletion region (Fig. A.3). With increased forward bias the depletion layer eventually becomes so thin that the electric field in the layer no longer can counteract charge carrier motion across the junction, larger and larger electric current will flow through the junction. Higher reverse bias instead leads to increasing electrical resistance and hence stops charge carriers from flowing. This is how a diode works, which allow flow of electric current in one direction but not in the other (Fig. A.4). By applying a reverse bias above a critical level the depletion zone will break down and a large current begins to flow. Breakdown may result in the destruction of a pn-device but this is not inevitable. For example if the current is kept small by an external resistance, damage can be avoided.

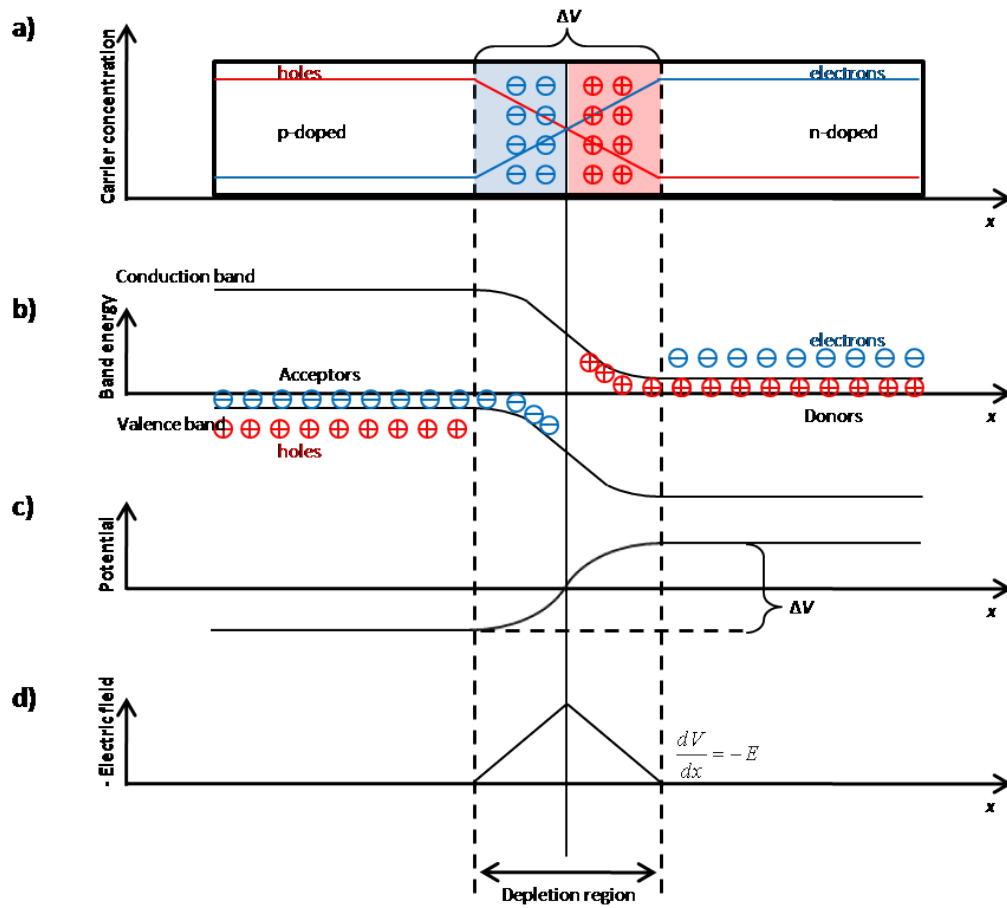
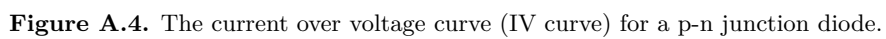
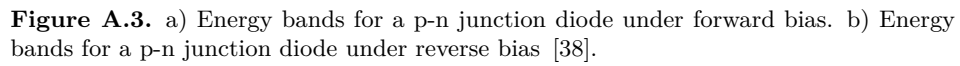


Figure A.2. A p-n junction in equilibrium without bias voltage applied. a) A sketch of the junction. b) The energy band model shows that there are doping atoms in the depletion region, but few free carriers (zero energy level is put to the Fermi level). c) The potential variation. d) The electric field [38].



Appendix B

Additional examples

B.1 Spherical mirror

Ex. B.1 shows that parallel incident light rays reflected off a spherical mirror will approximately cross at the focal plane of the mirror. Ideally parabolic mirrors should be used but they are harder to manufacture, measurements show that the geometry of spherical mirrors inside the RICH detectors provides a negligible contribution to the reconstructed Cherenkov angle precision.

Example B.1

In a first approximation a spherical mirror can be considered to be a parabolic reflector, that is all incoming light rays parallel to the optical axis are focused into the focal point, F , situated at half the distance of the radius of curvature $f = \frac{R}{2}$ on the optical axis. Consider a light ray reflected off a spherical mirror according to Fig. B.1 a) (in the 2-dimensional space). The incoming ray is reflected at a height h with a slope angle δ_{in} and the angle of incidence, with respect to the normal of the mirror in the reflection point, is α . The uppermost triangle, **A**, gives the following relation

$$\beta + \delta_{in} + \left(\frac{\pi}{2} - \alpha\right) = \pi \Rightarrow \alpha = \beta - \frac{\pi}{2} + \delta_{in}.$$

The second triangle, **B**, gives the relation

$$\gamma + \frac{\pi}{2} + (\pi - \beta) = \pi \Rightarrow \beta - \frac{\pi}{2} = \arcsin \frac{h}{R}.$$

The third triangle, **C**, gives the relation

$$\left(\frac{\pi}{2} - \alpha\right) + (\pi - \beta) + \delta_{out} = \pi \Rightarrow \delta_{out} = \beta + \alpha - \frac{\pi}{2} = 2\beta - \pi + \delta_{in} = 2 \arcsin \frac{h}{R} + \delta_{in}.$$

The reflected light ray is hence described by

$$y = h + \tan\left(\delta_{in} + 2 \arcsin \frac{h}{R}\right) \left(x - \sqrt{R^2 - h^2}\right) \quad (\text{B.1})$$

in a Cartesian coordinate system (x, y) . Assuming now a case where $h \ll R$ (the spherical mirrors of the LHCb RICH 1 - and RICH 2 detectors have radii of curvature $R_1 = 2700$ mm and $R_2 = 8600$ mm respectively) and that δ_{in} is small, we make the paraxial approximations $\sin \frac{h}{R} \approx \frac{h}{R}$ and $\tan\left(\delta_{in} + 2 \arcsin \frac{h}{R}\right) \approx \left(\delta_{in} + 2 \arcsin \frac{h}{R}\right)$, and also the approximation $\sqrt{R^2 - h^2} \approx R$. Equation B.1 is simplified to the easier

$$y = h + \left(\delta_{in} + 2 \frac{h}{R}\right) (x - R) \quad (\text{B.2})$$

Now assume we have two parallel incoming light rays with slope angle δ_{in} reflected at height h_1 and h_2 respectively (Fig. B.1 b)). Using equation B.2 the upper reflected light ray will follow $y = h_1 + \left(\delta_{in} + 2 \frac{h_1}{R}\right) (x - R)$ and the lower $y = h_2 + \left(\delta_{in} + 2 \frac{h_2}{R}\right) (x - R)$. The reflected light rays will cross when they have the same (x, y) coordinates and hence we put an equality between the formulas and get

$$h_1 + \left(\delta_{in} + 2 \frac{h_1}{R}\right) (x - R) = h_2 + \left(\delta_{in} + 2 \frac{h_2}{R}\right) (x - R) \Leftrightarrow x = \frac{R}{2}. \quad (\text{B.3})$$

The reflected light rays will cross at $x = \frac{R}{2} = f$ and $y = -\frac{R}{2} \delta_{in}$ at the focal plane.

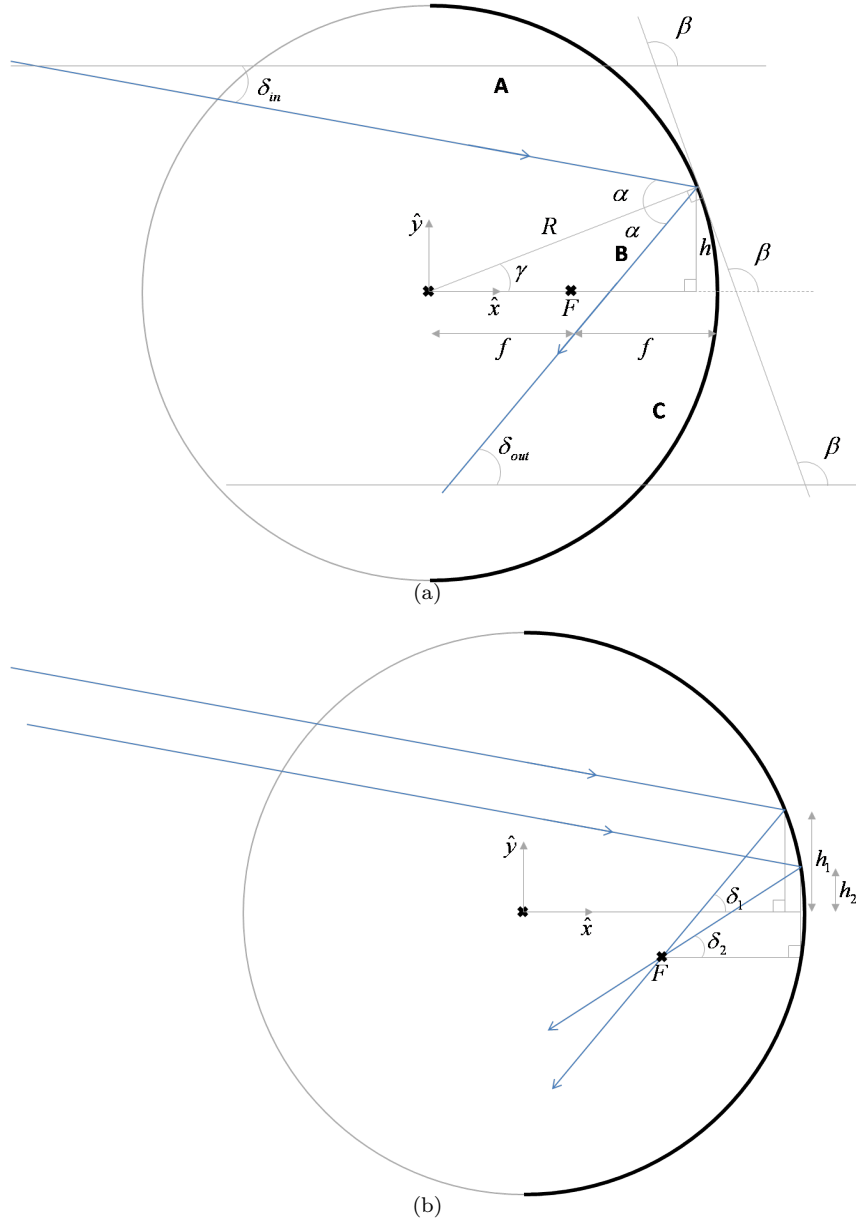


Figure B.1. a) Schematic drawing showing light ray tracing in a spherical mirror. b) Schematic drawing showing how two parallel incident light rays cross at the focal plane.

B.2 HPD model

Ex. B.2 is intended to provide the equations of motions for a charged particle in a cylindrical volume, with parallel electric - and magnetic fields directed along the symmetry axis (if the magnetic field is put to zero the equations become 1-dimensional). This is a highly approximate model of an HPD with perfect vacuum, used only to support some arguments in Chapter 3.

Example B.2

In a very first approximation an HPD can be modeled as a cylindrical volume with an electric field directed only along the symmetry axis, $\mathbf{E} = E\hat{z}$, and with perfect vacuum inside (i.e. no particle interactions). Assume now an applied magnetic field parallel to the electric field, $\mathbf{B} = B\hat{z}$, according to Fig. B.2. The photocathode in this model is situated in the x - y plane at the top of the cylinder.

Electrons escaping from photocathodes are of a Lambertian intensity distribution [20]

$$I = I_0 \cos \varphi_e \quad (\text{B.4})$$

where φ_e is the angle between the normal to the cathode plane and the direction of electron emission. The average emission angle is $\overline{\varphi_e} = \frac{\pi}{6}$ rad and the photoelectrons are emitted with a Maxwellian velocity distribution, their most probable emission velocity is

$$|\mathbf{v}_e| = \sqrt{\frac{2\overline{W}_{kin}}{m_e}}. \quad (\text{B.5})$$

m_e is the electron rest mass, $511 \text{ keV}c^{-2}$, and $\overline{W}_{kin}$ the average kinetic emission energy which depends on the incident photon energy.

Putting up the non-relativistic¹ equations of motion using the Lorentz force (Eq. 1.2) and Newton's second law $\mathbf{F} = m\frac{d\mathbf{v}}{dt}$, the following system is obtained for a charged particle of mass m and charge q :

$$\hat{x} : m\ddot{x} = qB\dot{y}$$

$$\hat{y} : m\ddot{y} = -qB\dot{x}$$

$$\hat{z} : m\ddot{z} = qE$$

where $x(t)$, $y(t)$ and $z(t)$ are functions of time. Let the particle be emitted with an angle φ and velocity $\mathbf{v}_p = -v_p \sin \varphi \cdot \hat{y} - v_p \cos \varphi \cdot \hat{z}$ where $v_p = \sqrt{\frac{2W_{kin}}{m}}$ and W_{kin} is the initial kinetic energy. Adjust the coordinate system so that the following initial conditions are valid: $x(0) = \frac{v_p \sin \varphi}{\omega}$, $\dot{x}(0) = 0$,

¹using the relativistic formula $W = \gamma m_e c^2$ with $W = 511 + 20 = 531 \text{ keV}$, from a 20 kV acceleration and $m_e = 511 \text{ keV}c^{-2}$, the Lorentz factor becomes $\gamma \approx 1.04$. Indeed non-relativistic calculations are appropriate on a photoelectron in an HPD. For a heavier particle, e.g. an ion, the Lorentz factor becomes even smaller

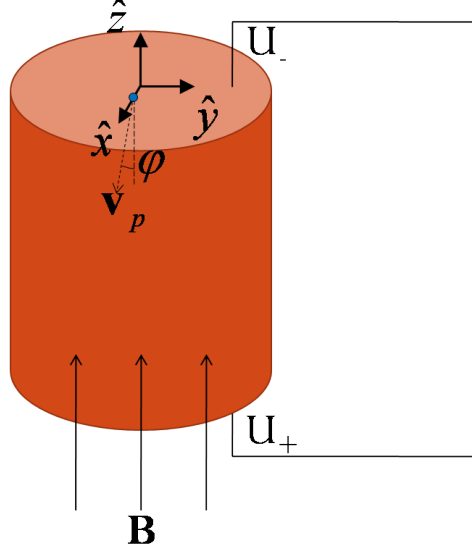


Figure B.2. A model of an HPD as a cylinder with a straight electric field inside. A magnetic field parallel to the electric field is applied.

$y(0) = 0$, $\dot{y}(0) = -v_p \sin \varphi$, $z(0) = 0$ and $\dot{z}(0) = -v_p \cos \varphi$. Then the particular solution becomes:

$$\begin{cases} x(t) = \frac{v_p \sin \varphi}{\omega} \cos \omega t \\ y(t) = -\frac{v_p \sin \varphi}{\omega} \sin \omega t \\ z(t) = \frac{qE}{2m} t^2 - v_p \cos \varphi \cdot t \end{cases}$$

where

$$\omega = \frac{qB}{m} \quad (\text{B.6})$$

is the Larmor frequency. The obtained helix trajectory will have a variable, increasing pitch and a radius

$$r = \left| \frac{v_p \sin \varphi}{\omega} \right| = \left| \frac{\sqrt{2W_{kin}} \sin \varphi}{qB} \right| \sqrt{m}. \quad (\text{B.7})$$

The line element is $ds = \sqrt{dx^2 + dy^2 + dz^2} = \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2 + \left(\frac{dz}{dt}\right)^2} dt = \sqrt{(v_p \sin \varphi)^2 + \left(\frac{qEt}{m} - v_p \cos \varphi\right)^2} dt$. ds is independent of B which means that the particle path length is independent of the magnetic field strength, an increased magnetic field will increase the Larmor frequency (Eq. B.6) but at the same time reduce the helix radius (Eq. B.7).

Let the applied voltage be U and the cylinder height d ($d \approx 110$ mm for an LHCb HPD [13]), then $E = \frac{U}{d}$. A negatively charged particle emitted at the

cathode ($z = 0$) will reach the anode ($z = -d$) at time

$$t_{trans} = \left(\frac{\sqrt{2W_{kin}} \cos \varphi}{qU} + \sqrt{\frac{2W_{kin} \cos^2 \varphi - 2qU}{q^2 U^2}} \right) d\sqrt{m} \quad (\text{B.8})$$

which is simplified to

$$t_{trans} = \sqrt{\frac{2}{|q|U}} d\sqrt{m} \quad (\text{B.9})$$

using zero initial kinetic energy, $W_{kin} = 0$. The transit time, t_{trans} , of the particle is proportional to $\sqrt{m}$. The following observations can be made: For a photoelectron in an HPD the initial kinetic energy is usually in the order of 1 eV which is small compared to an acceleration of 20 kV, the approximation $W_{kin} = 0$ is therefore appropriate. In the situation of a positively charged particle traveling from the anode to the cathode with opposite initial velocity the equation for the transit time (Eq. B.8) will be similar except for some changes in sign.

Appendix C

Additional figures

C.1 HPD ageing investigations

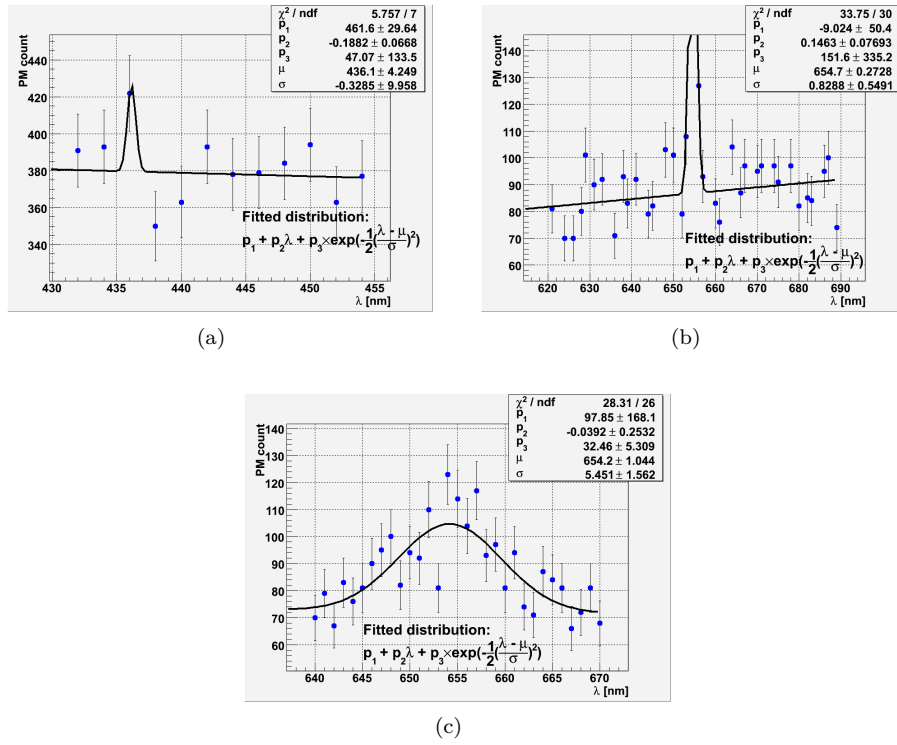


Figure C.1. a) Possible spectral line at 436 nm in glow light spectrum of H546003. b) Possible spectral line at 655 nm in glow light spectrum of H546003. c) Possible spectral line at 655 nm in glow light spectrum of H546004.

C.2 HPD image stability investigations

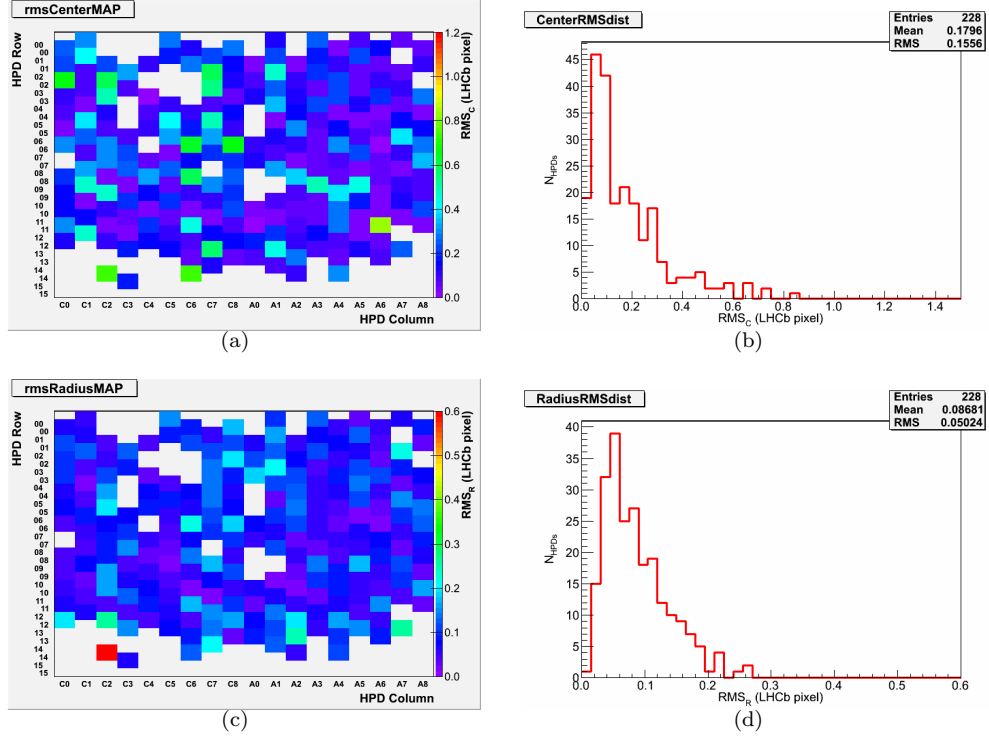


Figure C.2. a) HPD map of RMS_C values in a 57.0 h long laser run made in July 2009 (RICH2). White color means that the HPD was excluded from the analysis. b) Distribution of RMS_C values from the same run. c) HPD map of RMS_R values from the same run. d) Distribution of RMS_R values from the same run. C2_14 is missing in the distribution due to a very high value.

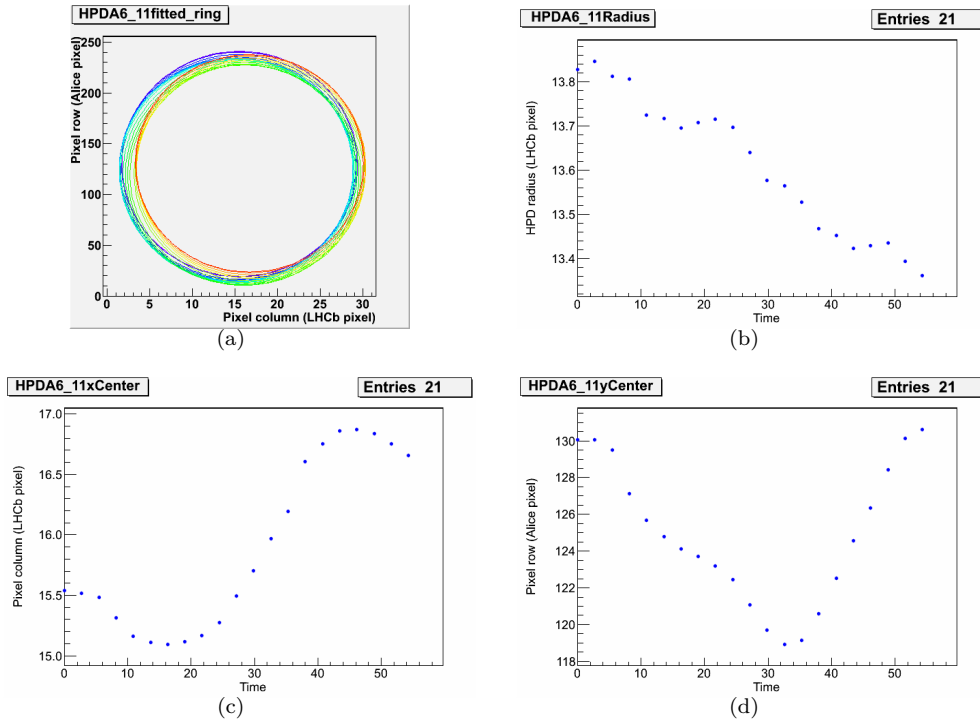


Figure C.3. a) HPD image shift in A6_11 in a 57.0 h long laser run made in July 2009 (RICH2). b) Calculated radius against time. c) Calculated center x -coordinate against time. d) Calculated center y -coordinate against time.

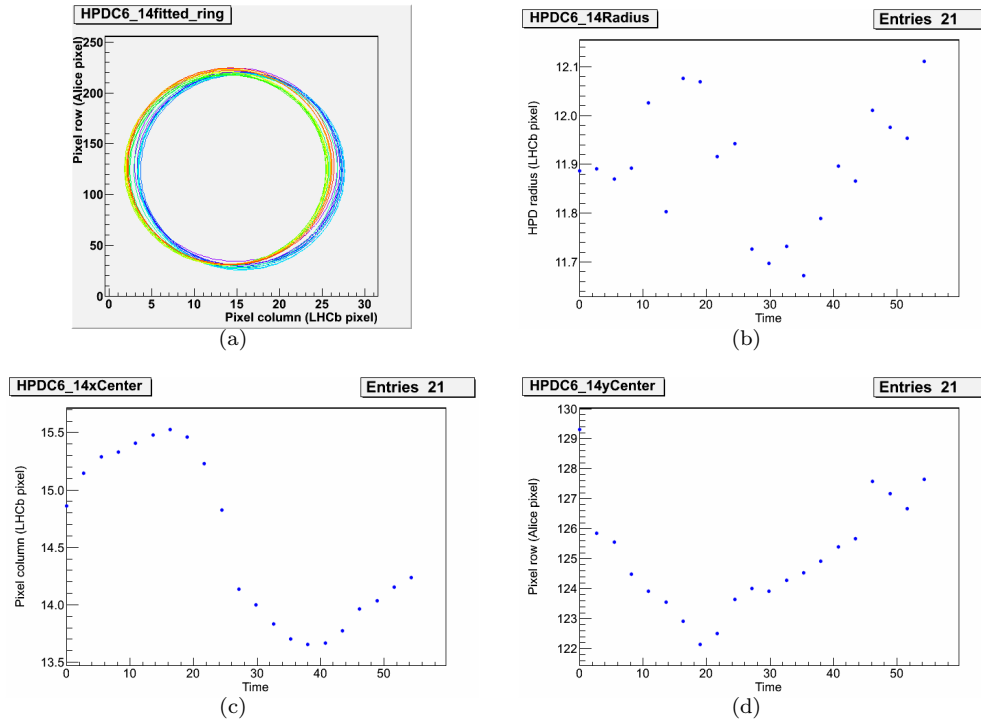


Figure C.4. a) HPD image shift in C6_14 in a 57.0 h long laser run made in July 2009 (RICH2). b) Calculated radius against time. c) Calculated center x -coordinate against time. d) Calculated center y -coordinate against time.

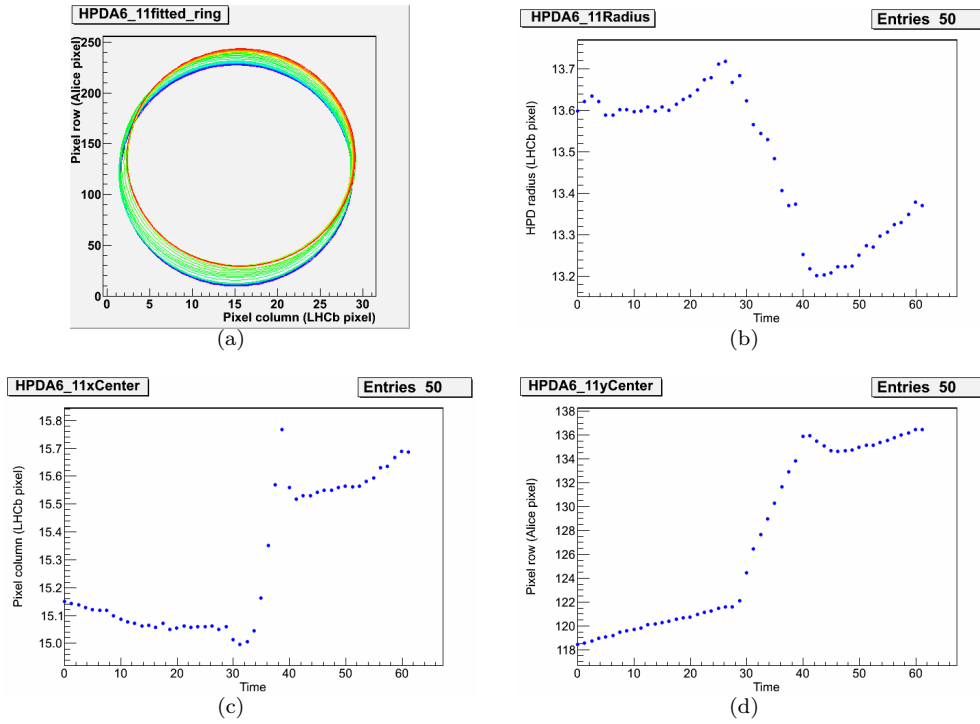


Figure C.5. a) HPD image shift in A6_11 in a 62.4 h long laser run made in August 2009 (RICH 2). b) Calculated radius against time. c) Calculated center x -coordinate against time. d) Calculated center y -coordinate against time.

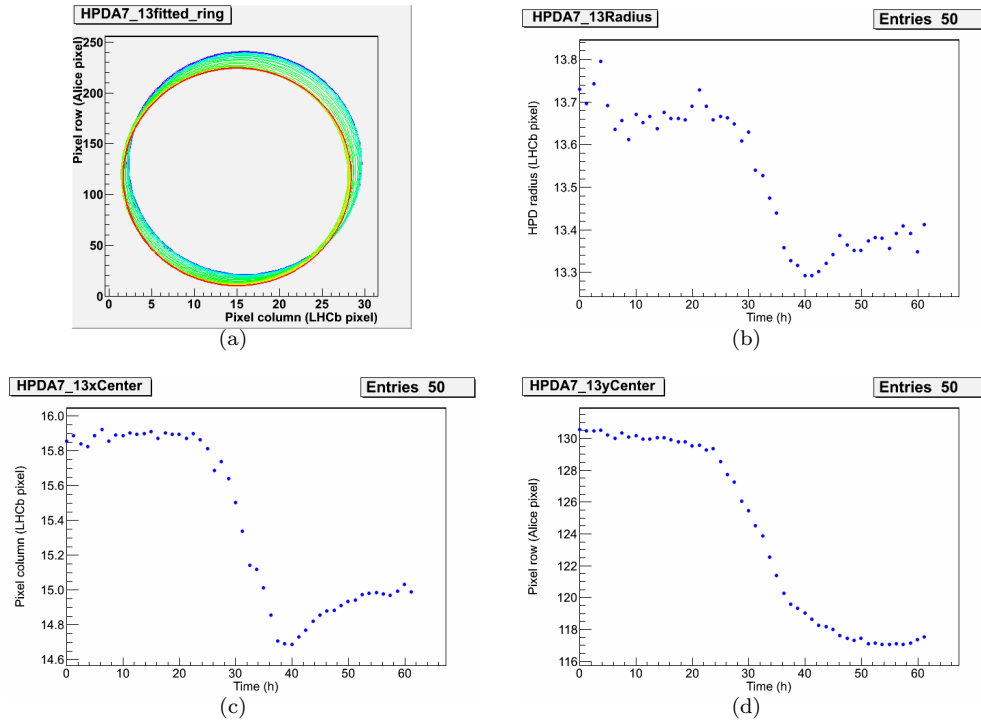


Figure C.6. a) HPD image shift in A7_13 in a 62.4 h long laser run made in August 2009 (RICH2). b) Calculated radius against time. c) Calculated center x -coordinate against time. d) Calculated center y -coordinate against time.

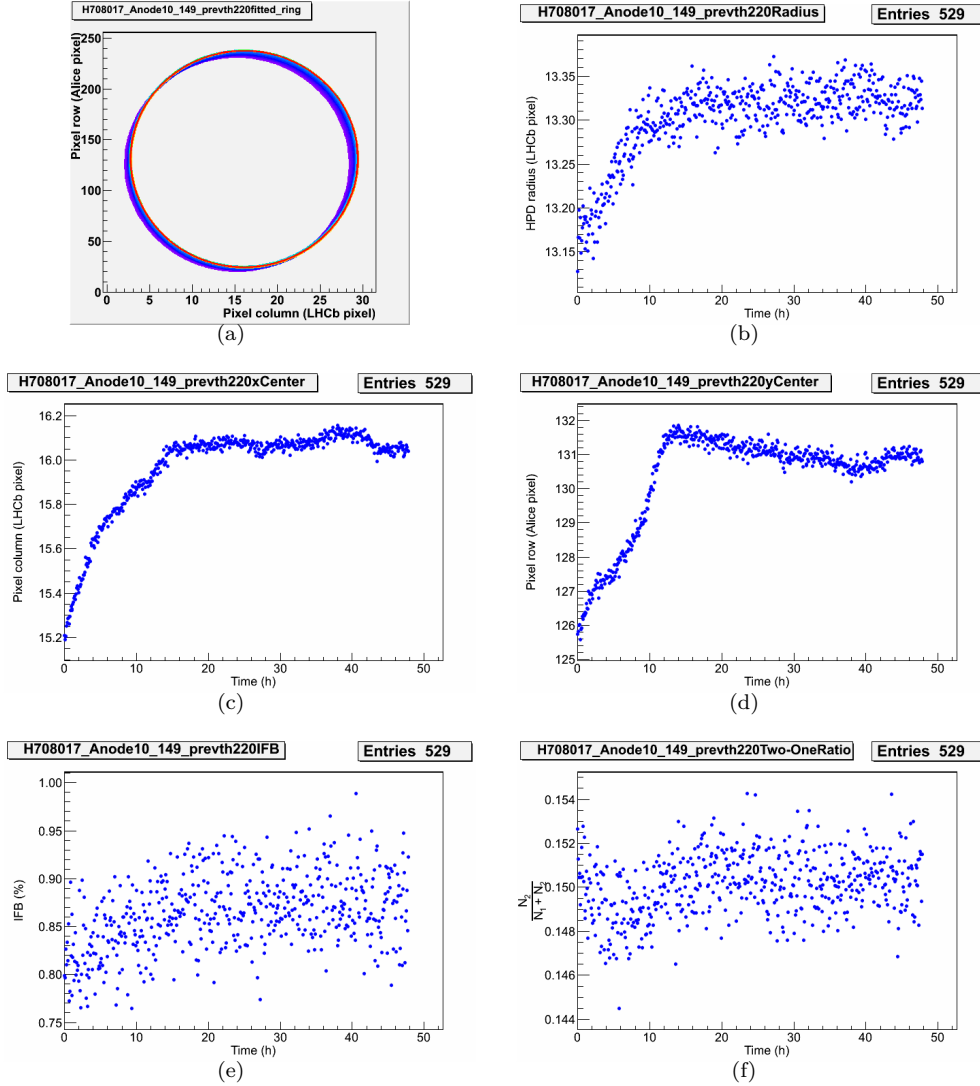


Figure C.7. a) HPD image shift in H708017 from a 48 h long run in November 2009, using a pencil LED and a widespread LED. 529 bursts of 20 000 events are analyzed as 529 time slices. b) Calculated radius against time. c) Calculated center x -coordinate against time. d) Calculated center y -coordinate against time. e) IFB rate against time. f) Two-to-one cluster ratio against time.

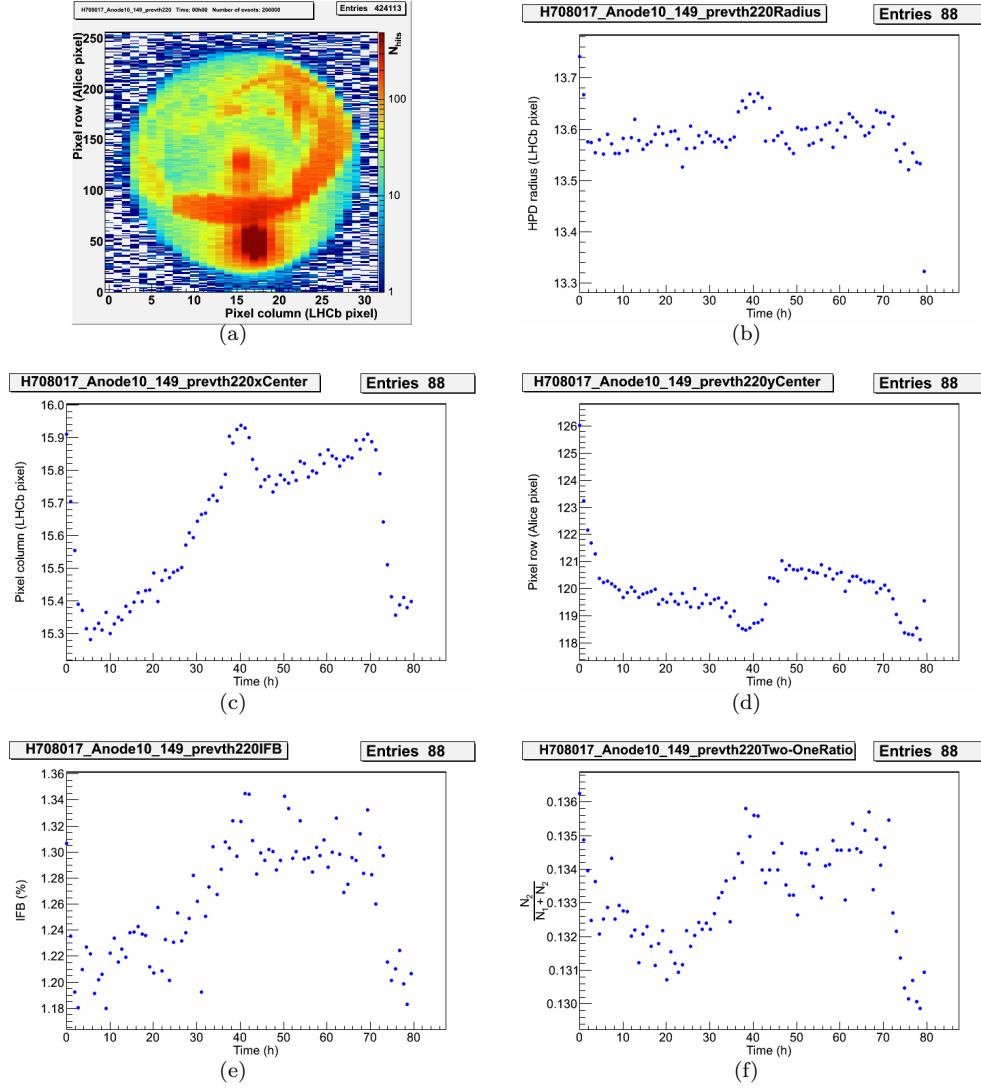


Figure C.8. a) Hitmap of first time slice from an 80 h long run in November 2009 with H708017, using a pencil LED and a widespread LED. 876 bursts of 20 000 events have been merged into groups of 10, making 88 time slices. b) Calculated radius against time. c) Calculated center x -coordinate against time. d) Calculated center y -coordinate against time. e) IFB rate against time. f) Two-to-one cluster ratio against time.

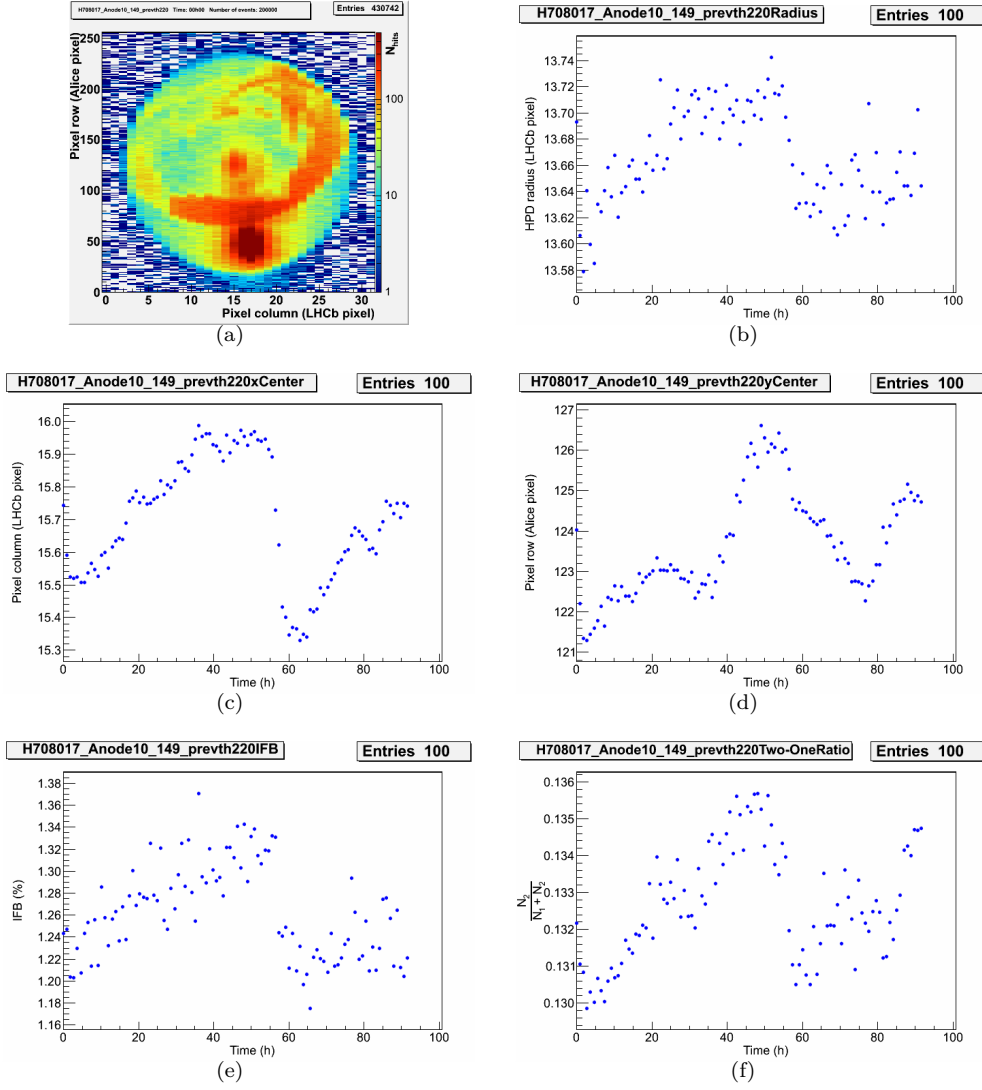


Figure C.9. a) Hitmap of first time slice from a 92.5 h long run in November 2009 with H708017, using a pencil LED and a widespread LED. An extra ground cable was connected to the HPD. 1000 bursts of 20 000 events have been merged into groups of 10, making 100 time slices. b) Calculated radius against time. c) Calculated center x -coordinate against time. d) Calculated center y -coordinate against time. e) IFB rate against time. f) Two-to-one cluster ratio against time.

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