Characterization of the Hamamatsu R11265-103-M64 multi-anode photomultiplier tube for the LHCb RICH upgrade

M. Calvi\textsuperscript{ab}, P. Carniti\textsuperscript{ab}, L. Cassina\textsuperscript{ab}, A. Giachero\textsuperscript{ab}, C. Gotti\textsuperscript{ab}, B. Khanji\textsuperscript{a}, M. Maino\textsuperscript{ab}, C. Matteuzzi\textsuperscript{a} and G. Pessina\textsuperscript{ab}.

\textsuperscript{a} INFN, Sezione di Milano Bicocca, Piazza della Scienza 3, 20126, Milano, Italy
\textsuperscript{b} Dipartimento di Fisica G. Occhialini, Università degli Studi di Milano Bicocca, Piazza della Scienza 3, 20126, Milano, Italy

Abstract

The Hamamatsu R11265-103-M64 MaPMT is the baseline photon sensor to be used for the LHCb RICH Upgrade detector. This choice has been supported by a large number of tests of this device. This note summarizes the measurements performed by the INFN Milano Bicocca group to characterize the photon detector. A description is provided of the unpublished outcomes and particularly of the more recent developments about the aging of the R11265-103-M64 MaPMT and the test of a whole photon detector RICH Elementary Cell.
1 Introduction

The LHCb detector has operated at a luminosity of $4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ so far, although the LHC would be able to supply higher luminosity. In order to make the detector capable to run at luminosities of $2 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$ (providing 5 fb$^{-1}$ per year), an upgrade of the whole LHCb detector is needed [1]. The Ring Image Cherenkov (RICH) system, which provides particle identifications (PID) of charged hadrons over a large momentum range, is planned to be upgraded after 2018. Although the overall structure of both RICH detectors will remain unchanged, significant modifications are required. As far as the RICH photodetectors are concerned, the HPD used so far will be replaced by Multi-anode PhotoMultiplier Tubes (MaPMTs) coupled with external wide-bandwidth readout electronics. A complete characterization of the Hamamatsu $R11265-103-M64$ MaPMT has been performed by the INFN Milano Bicocca group at the Milano Bicocca University. These measurements led the LHCb collaboration to choose such device as the baseline photon detector for the RICH upgrade, as described in [2]. Most of the results of the characterization have recently been published in Journal of Instrumentation [3] and they are briefly summarized in the first sections. Particular attention is paid to the behaviour of the device in a magnetic field (section 3) and to its capability to operate for long period of light exposure (section 4). New measurements have been made in order to test the performance of a whole photosensitive Elementary Cell (a $2 \times 2$ $R11265-103-M64$ matrix) while operating under the influence of a longitudinal magnetic field. The setup, the results obtained and their comparison with the RICH requirements are described in section 5.

2 Standard single device characterization

The $R11265-103-M64$ is a 64-channel ($8 \times 8$) pixel device with an active area of $23 \times 23 \text{mm}^2$, a pixel size of approximately $2.9 \times 2.9 \text{mm}^2$ and able to detect single photons. A very small inactive border around the device ensures a total active area coverage of about 77%, while the MaPMT square cross-sectional geometry allows for a close packing ratio (approximately 90%). These features make this device suitable for a RICH detector. The outcomes of the effort made for the $R11265-103-M64$ characterization by the Milano Bicocca group have been described in [3]. The most significant results with respect to the LHCb requirements are summarized in this section.

Fig. 1 shows the superposition of the single photon spectra acquired in several pixels of the $R11265-103-M64$ MaPMT. The capability of the device to operate in single photon regime is confirmed for almost all pixels. The typical gain spread among the pixels amounts at a maximum to 2.5, in agreement with the uniformity table provided by Hamamatsu. In fig. 2 the anode response of the maximum gain pixel is plotted as a function of the supply high voltage for the four available devices. In particular, the average gain with $HV = 1 \text{kV}$ amounts to $\sim 2 \text{Me}^{-}$. The gain and the dark counts noise of the $R11265-103-M64$ MaPMT was studied as a function of the temperature by using a climatic chamber. It was estimated that the gain

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Figure 1: The single photon spectra for several pixels (bias voltage equal to -950 V).

Figure 2: The single photon response versus the MaPMT bias voltage for the pixel with the maximum gain in each tube.

reduces almost linearly by about 5.5 keV/°C (or, equivalently, a gain variation of about 0.3% per °C assuming 30 °C as reference value) [3]. Indeed, increasing the temperature the mean free path of the secondary electrons inside the dynodes decreases so that a smaller number of electrons is able to escape from the dynode surface and take part in following multiplication steps. It follows that the MaPMT gain decreases.

While the typical dark count rate at room temperature is 5 Hz per pixel (i.e. ~ 60 Hz/cm²), the noise turned out to be strongly dependent on the temperature. For instance, the dark current rate at 50 °C is about 30 times greater than the one at −30 °C (fig. 3). The reason of this phenomenon is that, increasing the temperature, the number of electrons which have enough thermal energy to escape from the dynodes or the photocathode surface and generate a multiplication process increases.

Another important requirement which the R11265-103-M64 MaPMT has to fulfill is to ensure a low cross-talk level. Simultaneously with the main signal, a cross-talk pulse was observed in the neighbouring pixels. As shown in fig. 4, the cross-talk signal consists of a small oscillation with a period of about 4 ns and amplitude of ~ 5% – 10% with respect to the main pulse.

3 Behaviour in a magnetic field

As the MaPMT is supposed to be employed in the RICH-1 detector where a fringe DC magnetic field is expected, the behaviour of the device has to be tested in this critical environment condition. Indeed, in principle the performance of a photomultiplier tube can be affected by an external magnetic field since it might induce some electrons moving from one dynode to the following one to change their trajectory. According to the preliminary conclusion described in [4], the highest magnetic field expected in the RICH-1 detector amounts to ~11 G. In a very conservative approach, the R11265-103-M64 performance
was tested under the influence of a magnetic field up to 100 G produced by a solenoid. Similarly to the results already obtained studying the R7600 MaPMT\cite{5}, the main effects are induced by a longitudinal magnetic field (parallel to the tube axis). The central pixels are quite insensitive to the external magnetic field since the metallic lateral surface of the device is able to deflect the field lines reducing the magnitude of the magnetic field in the central region. As shown in fig. 5(a), the single photon spectrum of the central pixel 46 is weakly distorted even by a 50 G field. On the contrary, the lateral pixels are strongly affected, especially those near the biasing pins (i.e pixels from 1 to 8 and from 56 to 64). Figure 5(b) shows that in these worst cases even 25 G might cause the pixel turning off and the photon detection efficiency decreasing by 40% (the photon detection efficiency, $\epsilon$, has been defined as the rate of events whose amplitude is larger than a noise level of $0.2 \text{ Me}^{-}$). The results suggest that the R11265-103-M64 needs to be shielded in order all the pixels to work properly in a magnetic field.

Therefore, shields made of high magnetic permeability material were considered in order to absorb the magnetic field. In particular, the performance of the R11265-103-M64 MaPMT were tested while shielded by a layer of Skudotech\textsuperscript{®} ($\sim 200 \mu\text{m}$ thick, nominal maximum magnetic permeability $3.27 \cdot 10^5$, produced by SELITE) wrapping the MaPMT lateral surface. As shown in fig. 6(a), even the most sensitive pixels are recovered for fields up to 25 G by shielding the device with a single Skudotech\textsuperscript{®} layer which protrudes from the photocathode surface by at least $\sim 1 \text{ cm}$. While larger protrusion lengths do not provide better performance, the shield effectiveness decreases if it does not protrude enough from the photocathode surface. Note that, in case of higher fields, thicker shields should be considered to prevent the loss of their effectiveness due to the saturation effect (fig. 6(b)). Further information on these measurements can be found in \cite{3}. 

\textsuperscript{1}\url{http://www.bmtel.it/Skudotech.pdf}
Figure 5: Superposition of single photon spectra acquired under the influence of different longitudinal magnetic fields values. (a) refers to pixel 46 located in the central part of the MaPMT while (b) corresponds to pixel 62 in the peripheral region, just near the biasing high voltage pins ($R11265-103-M64$ biased at -1050V.)

Figure 6: Superposition of single photon spectra acquired with the MaPMT $R11265-103-M64$ under the influence of a longitudinal magnetic field using shields which differ in the protrusion length. All the plots refer to pixel 62, located on the side of the device, just next the biasing high voltage pins. The magnetic field ranges from 25 G (a) to 50 G (b).

4 Aging test

Long periods of light exposure may deteriorate the MaPMT nominal performance due to the wear off of the multiplication dynodes and the photocathode. Thus, a fully automatic system $^{3}$ was set up in order to estimate how the light exposure affects the $R11265-103-M64$ performance. The most significant effect due to aging turned out to be
the loss of the MaPMT gain, evaluated by measuring the single photon peak amplitude over a \( \sim 3000 \) hours operation period. This is equivalent to about two years of LHCb RICH operation considering that the average effective LHCb operation time over 2011 and 2012 amounted to about 1500 hours per year\(^2\) Note that the MaPMT aging started after maintaining the device at dark for three days and that the gain loss is evaluated considering the gain after few hours of LED illumination as the initial condition.

Although the main setup conditions of the measurements was kept almost unchanged, the gain variation turned out to be significantly different from one device to another. According to the manufacturer, such a behaviour could be correlated with the variation of several design parameters which are usually tuned during the first production phases between devices with different serial numbers. In particular, the crucial parameter to be taken into account is the thickness of the Cesium layer grown upon the dynodes surface. Such a layer is necessary in order to allow the low energy secondary electrons to escape from the dynode surface via tunnel effect. On the other hand, an excess in the Cesium thickness would lead to a lower probability of secondary electron emission. In this condition, the wear off of the dynodes surface due to long operation periods would result in a reduction of the excess Cesium and in an increase of the photon detector gain.

So far, the aging tests were performed on four \textit{R11265-103-M64} MaPMTs with different serial numbers. The very first results were described in [6] and are referred to one of the first devices produced by Hamamatsu (serial code: ZN0170). Unexpectedly, the gain loss seems not to be correlated with the integrated charge of the pixels (or similarly to the occupancy level) but only with the LED illumination time, so the gain variation does not depend on the illumination intensity (fig. 7). After the first 500 h, the gain loss is about 10%. After that, a quite linear trend with a gain variation rate of about 120 ppm/h can be observed until about 1500 h of illumination are reached. Then the plateau can be seen: the response stabilizes and the total gain loss amounts to about 25%.

Note that the ZN0170 MaPMT was already used in some other measurements before the aging test, including the test beam performed on November 2012. Moreover, the setup used for these measurements was not able to keep stable the temperature so that it ranged from 19.5\(^\circ\)C to 26\(^\circ\)C during the test. These could be the reason of such surprising behaviour. In order to prevent the temperature variations from affecting the later tests, the setup was equipped with an automatic system which continuously monitored the temperature, keeping it stable at 25\(^\circ\)C (maximum variation 0.06\(^\circ\)C).

After this setup improvement, a second \textit{R11265-103-M64} MaPMT was tested (serial code: ZN0707). As expected, the gain loss strongly depends on the DC aging current flowing in each observed pixel (fig. 8) or, equivalently, to the occupancy level (\( \theta \)) defined as the rate of single photon events occurred in one pixel with respect to the proton-proton collision rate\(^3\). In particular, the gain loss of the most illuminated pixel (\( \vartheta \approx 38\% \)) falls down by \( \sim 60\% \) after only 1200 hours. Similarly, this initial sharper decrease can be

\[^2\]For detailed information: [https://lhc-statistics.web.cern.ch/LHC-Statistics](https://lhc-statistics.web.cern.ch/LHC-Statistics)

\[^3\]The occupancy (\( \theta \)) can be estimated measuring the DC aging current (\( I_{DC} \)) and using the equation \( \theta = I_{DC} / (R_P \cdot G \cdot q_e) \), where \( R_P \) is the proton-proton collision rate, \( G \) is the gain of the pixel and \( q_e \) is the electron charge.
observed also for the other channels with a DC current larger than 1 $\mu A$ ($\theta > 10\%$). After about 1200 hours, the gain variation reduces, then remains almost stable. Considering that in the central zone of the RICH-1 detector the maximum expected occupancy is $\theta_{\text{max}} \simeq 20\%$, the gain loss after 3000 hours would amount to $\sim 50\%$.

![Figure 7: Gain variation (in %) versus the illumination period for the first tested MaPMT (ZN0170). For these measurements the setup was not equipped with the temperature stabilization system.](image1)

![Figure 8: Gain variation (in %) versus the illumination period for the second tested MaPMT (ZN0707).](image2)

Given the inconsistency of the previous tests and in order to enlarge the statistics, the INFN Milano Bicocca group purchased five more brand new $R11265-103-M64$ MaPMTs with similar serial code and recently produced by Hamamatsu. Two devices have been tested so far (serial code: FA0025 and FA0026) keeping almost unchanged the abovementioned setup conditions. All the pixels were illuminated with a similar light exposure ($11.2\% \leq \theta \leq 21.9\%$) which corresponds to the maximum integrated current sustainable by the tube ($100\, \mu A$). The gain variation as a function of the LED illumination time can be observed in fig. 9 (FA0025) and fig. 10 (FA0026, tested for $\sim 1300$ hours). As expected, all the channels show a similar behaviour. As soon as the FA0025 MaPMT is illuminated (fig. 9), an initial sharp gain loss by several percentage points can be observed (within $\sim 150$ hours of LED illumination). After that, the gain starts to increase almost linearly and with a similar slope for all the observed channels ($\sim 50$ ppm/h). Although in the last section of the tests some setup failures occurred, the trends seems to be maintained until $\sim 3000$ hours. A very similar behaviour can be also observed in fig. 10 referred to the FA0026 MaPMT. After the first several hours, a linear gain recovery is noticeable for all the tested pixels and this trend is compatible with the one previously described for the FA0025 MaPMT. It can be noticed that some pixels show a final gain larger than the starting value, while others have not recovered the initial performance completely. Anyway, the average gain variation over the observed pixels turns out to be negligible (lower than 1%).
Summarizing, the first tests showed a gain loss higher than the expectation. However, even the most illuminated pixel ensured a single photon gain larger than 0.7 Me−/photon after the aging and the single photon peak could be still clearly resolved from the pedestal. The standard method to compensate such an aging effect is to increase the bias voltage. It turned out that increasing the high voltage by only 25 V (from -1000 V to -1025 V at 1917 hours) a gain loss of 10-15% could be compensated for almost all the channels [3]. On the other hand, the last measurements suggested that the latest generations of the R11265-103-M64 (the FA series) better sustains long period of light exposure, even when operating at the maximum integrated current.

![Figure 9: Gain variation (in %) versus the illumination period for the third tested MaPMT (FA0025).](image)

![Figure 10: Gain variation (in %) versus the illumination period for the fourth tested MaPMT (FA0026).](image)

5 Test of the Elementary Cell

As described in details in [2], a modular arrangement has been designed for mounting the R11265 tubes and the front-end readout boards. Due to the large number of MaPMTs, the modular structure must fulfill several requirements such as the close-packing on a large surface, an easy access for repair and maintenance, the structural stability, the thermal dissipation and the incorporation of electrical and electromagnetic insulation and electrical connections from/to the MaPMTs. The current modular structure is based on the Elementary Cell (EC) assembly, which consists of 2 × 2 MaPMTs.

The goal of these measurements is to test the R11265-103-M64 performance under the action of a longitudinal magnetic field using a single shield wrapping the whole Elementary Cell instead of each device of the matrix (fig. 11). Besides the practical advantages, a single shield would ensure a lower shading of the MaPMTs and a larger photon angular acceptance as well. Fig. 12 shows the custom 2 × 2 socket developed in Genova for the R11265 MaPMTs [7]. The devices are oriented in order to satisfy a radial symmetry with respect to the center of the socket, so that pixel 1 is near the center of the
EC for each MaPMT, as well as pixel 64 is always located at the corner of the matrix (fig. 12). Thanks to the radial symmetry, each R11265-103-M64 MaPMT is perturbed by a longitudinal magnetic field independently on its position inside the matrix. For instance, pixel 64 is always in the corner of the cell and just near to the shield, so that both the longitudinal magnetic field and the shield will act in the same way on all these pixels of the cell for each tube. Thus, we can restrict to study only one R11265-103-M64 MaPMT of the matrix and extend the results to the other MaPMTs of the Elementary Cell.

The setup is the same used for the single device characterization [3]. The whole MaPMT matrix was wrapped by a single Skudotech® layer protruding ~1 cm from the photocathode surface (fig. 11). Following the expected mechanical constraints, the anode pins were not shielded. A commercial blue LED, which was biased with a very low voltage so that it operated in a single photon regime, illuminated the matrix. The longitudinal magnetic field, produced by a solenoid, ranged from 0 G up to 25 G (the maximum field expected in RICH-1 detector is ~11 G [4]). As already mentioned, only a single MaPMT of the cell was biased at -1050 V, corresponding to an average gain of about 4 Me−/photon. The R11265-103-M64 signal was amplified using a classic charge sensitive preamplifier circuit and finally acquired by a DT5720 CAEN Desktop Digitizer.

\[4\text{The DT5720 is a 4 channel 12 bit 250 MS/s Desktop Waveform Digitizer with 2 Vpp single ended input. The DC offset is adjustable via a 16 bit DAC on each channel in the ±1 V range.}\]
fixing a trigger threshold of $\sim 60$ ke$^-$. 

Figure 13: Each graph shows the superposition of single photon spectra acquired under the action of a longitudinal magnetic field. The plots show the results for four pixels of one of the tubes of the matrix cell. The shield wrapping the whole matrix was made of a single Skudotech® layer which protrude 1 cm from the photocathode surface. Pixels 2, 58 and 62, located just on the side of the biasing high voltage pins, represent the worst case conditions.

Fig. 13 shows the single photon spectra obtained for four pixels at various magnetic field values. Most of the pixels behave similarly to pixel 48 (top-right plot): the distortions are negligible and no loss of efficiency is observed in these pixels even at 25 G. In agreement with what summarized in the previous section, the most sensitive pixels turned out to be those near the biasing high voltage pins (i.e. pixels 1 to 8 and 56 to 64). The shield works satisfactorily so that the loss of efficiency at 10 G becomes almost negligible ($\sim 2\%$), while it rises to $\sim 20\%$ at 25 G. It was also demonstrated in [3] that thicker shields can be used in order to achieve a more effective absorption of the external magnetic field.

6 Conclusions

The INFN Milano Bicocca group has tested several R11265-103-M64 multi-anode photomultiplier tubes produced by Hamamatsu [3], the baseline photon detectors for the LHCb RICH upgrade.
The results on the cross-talk and the dark signal rate have shown that this photomultiplier tube fulfills the LHCb RICH upgrade requirements. The phototube performance has been studied also as a function of the bias voltage and temperature. A pixel-to-pixel gain spread of about a factor 2.5 has been observed, which suggests to couple the phototube with a read-out electronics able to compensate this effect \cite{8}.

A R11265-103-M64 MaPMT has been tested with respect to the behaviour in a magnetic field up to 100 G. With a proper high magnetic permeability shielding material, the device can operate well under the influence of the magnetic field expected in the RICH-1 detector. The behaviour of an Elementary Cell has also been studied in case of a longitudinal magnetic field up to 25 G. An unique single layer shield turned out to properly absorb the magnetic field so that only negligible effects have been observed at 10 G.

The gain variation, the increase of dark signal rate and the loss of the photocathode efficiency due to the aging have been studied \cite{3}. The main aging issue has turned out to be the gain variation, effect which can be compensated by adjusting the bias voltage. The latest generations of R11265-103-M64 MaPMT are able to sustain long period of light exposure even when operating at the maximum integrated current.

References


