Performance of the photomultiplier tubes used in the DIRC of BABAR: effect of a magnetic field and of helium

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Abstract

This presentation summarizes the measurements performed on the ETL 9125FLB17 photomultiplier tubes, used in the particle identification device of the high energy physics BABAR experiment. In particular, we show how the performance of the phototubes is degraded by either a magnetic field or helium gas.

1 Introduction

The BABAR experiment [1] is designed to study CP violation in the B meson system at the SLAC PEP-II asymmetric e^+e^- collider. It uses a new type of detector for particle identification, a DIRC [2] (Detection of Internally Reflected Čerenkov light). In this device, a charged particle produces Čerenkov light when traversing a quartz bar. The type of the particle is characterized by the emission angle of the Čerenkov photons. The light is carried through internal reflections to the ends of the bar, thus preserving the angular information. It then goes across an expansion region of very pure water, with about the same index of refraction as the quartz, to a toroidal surface, covered by 10752 photomultiplier tubes (PMTs) staying in the water.

The PMTs are arranged in a closely packed array and equipped with light catchers in order to maximize the detection area. As Čerenkov radiation is a weak source of photons, the PMTs work in single photoelectron (p.e.) detection mode. A high quantum efficiency and sufficient gain are desired to detect photons efficiently in the visible and near-UV range. A good timing

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resolution and low dark noise rate help to reduce the background. The ETL 9125FLB17 PMT [3] manufactured by Electron Tubes Limited, previously known as Thorn-EMI, was chosen from several types of PMTs [4,5]. It is a cylindrical phototube with a diameter of 28.2 mm. It has eleven stages of amplification with a linear focus structure. Its bialkali photocathode is planar with a mean sensitivity in the blue, measured using a standard Corning CS5-58 filter, of 11.5 μAmp/lumen-blue for our sample. Its envelope is made out of a special borosilicate glass, resistant to very pure water.

In the *BaBar* environment, like in many high energy physics experiments, the performance of phototubes may be degraded by two hazards, which we want to quantify. The first one is the fringe field outside the iron flux return of the 1.5 T magnetic field created by the solenoid of *BaBar*. The behavior of the PMTs in a magnetic field had to be known for the design of a soft iron shield [6]. The second one is helium leakage, from either the gas of the drift chamber or the cryogenic system of the supraconducting coil. Helium is known to enter phototubes, thus destroying the vacuum and making them useless.

Section 2 gives the basic performance of the PMT. Section 3 deals with the results in a magnetic field, while section 4 studies the effect of helium.

2 Performance of the PMTs

The basic characteristics of our PMTs were checked on a statistical basis, to control their good quality [7]. 1283 phototubes have been tested, i.e. 12% of the whole sample of 10880 ordered PMTs. The working high voltage, peak-to-valley ratio, timing resolution, dark noise rate and active size of the photocathode were measured. In addition, some mechanical tests were performed on all PMTs : visual control of the photocathode and the pins, measurement of the PMT length and diameter and of the pin concentricity. About 1% of the PMTs failed the mechanical tests and were exchanged or repaired by ETL.

Two light sources have been used. Both are blue diodes with a wavelength of 450 nm pulsed with a time resolution of about 0.7 ns [8]. The intensity of the first one is set at 0.3 p.e. per pulse, in order to work in single p.e. detection mode. The whole photocathode is illuminated thanks to a diffuser. The second one, used only for the scan of the photocathode, has a greater intensity, about 100 p.e. per pulse. A collimator with a diameter of 0.5 mm allows the illumination of a precise point of the photocathode. Both light sources can be moved automatically, with an accuracy of 0.1 mm, to be placed in front of or scan each PMT. A positive high voltage with a 3.63:1:1... voltage divider is applied to the PMT. Its signal is sent to an ADC for measurement of the charge and a TDC, via a Constant Fraction Discriminator with an adjustable threshold, for timing measurement. The acquisition program is based on LABVIEW. A large part of the testing is done in an automatic way. Given the large number of PMTs to test, this was highly desirable. An example of ADC and TDC spectra is shown on figure 1.

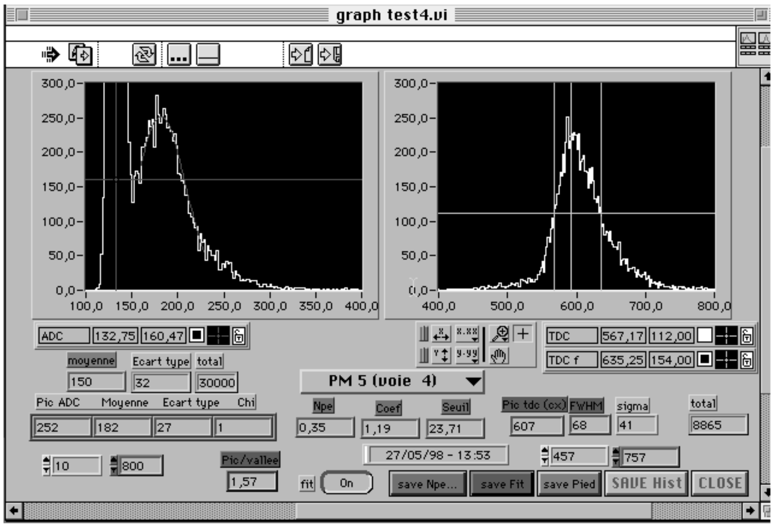

Fig. 1. View of the charge distibution measured in the ADC (left) and of the time distribution measured in the TDC (right).

The working high voltage, used in all subsequent measurements, is defined as the one which gives an amplitude for the single p.e. signal of 20 mV. It is measured with a digital oscilloscope. A correction is applied for the small fraction of pulses with two or more p.e. and the effect of the threshold set at 3 mV, 15% of the signal. The single p.e. amplitude is equivalent to a charge gain of about 1.7×10^7, assuming that the pulse shape is the same for all phototubes. The pulse shape was found to be fairly constant on all tested PMTs. As shown on figure 2a, the working high voltage of all PMTs is in the range from 900 to 1400 V. It is well below the maximum high voltage of 1600 V guaranteed by the manufacturer for our operating conditions.

To detect the single p.e., the PMTs should have a good peak-to-valley ratio, illustrated in the ADC spectrum on the left part of figure 1. It is the ratio of the peak of the single p.e. charge distribution to the valley located between this peak and the falling tail corresponding to the zero p.e. and the first dynode p.e. As shown on figure 2b, the average peak-to-valley ratio is 2.07.

A good timing resolution is necessary to remove random backgrounds. The timing resolution is obtained from the full width at half maximum (FWHM) of the distribution measured in the TDC, illustrated on the right part of figure 1. The distribution is non Gaussian because the transit time depends on the impact point on the planar photocathode [4]. Figure 2c shows the distribution of the timing resolution, defined as σ = FWHM/2.35 and corrected for the timing resolution of the light source. The average value is 1.5 ns.

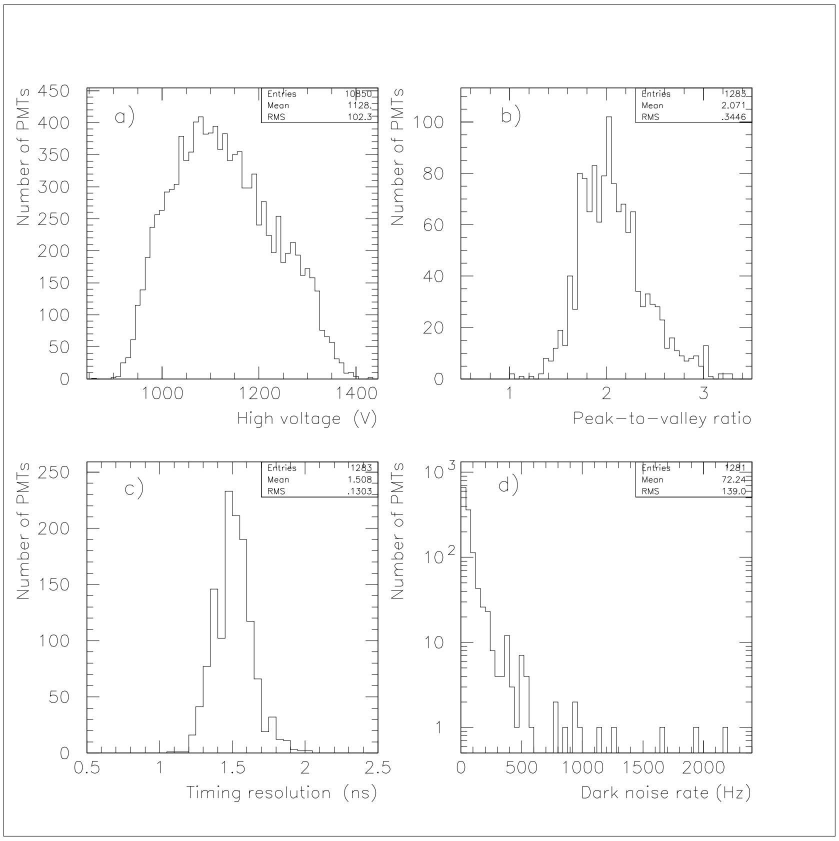

Fig. 2. Distributions of the working high voltage for all (10880) phototubes (a), the peak-to-valley ratio (b), the timing resolution (c) and the rate of dark noise (d) for all (1283) tested phototubes.

The dark noise rate is defined as the number of counts above threshold per second while the PMT has been in the dark with the high voltage on since several hours. Figure 2d shows its distribution, measured with a threshold of 4 mV. The mean value is 72 Hz. All PMTs have an intrinsic noise well below the expected rate of random photons from the accelerator, about 100 kHz.

The scan of the photocathode allows the control of its effective size. The PMTs are scanned, with a step of 0.5 mm, along the most favorable direction, parallel to the dynodes, since the useful area is not absolutely circular. With a light intensity of about 100 p.e. per pulse, the ADC spectrum is Gaussian. Its mean value, after subtraction of the pedestal, measures the photon detection efficiency, whose distribution as a function of the coordinate of the illuminated point is illustrated on figure 3 (top curve). The useful diameter is defined as the length over which the photon detection efficiency exceeds 75% of its central value, calculated using the points within 5 mm of the center. Furthermore the RMS of the measured efficiencies within the useful diameter provides an estimate of the inhomogeneity of the photocathode. As shown on figure 4, we find on average a useful diameter of 25.8 mm and an inhomogeneity of 4%.

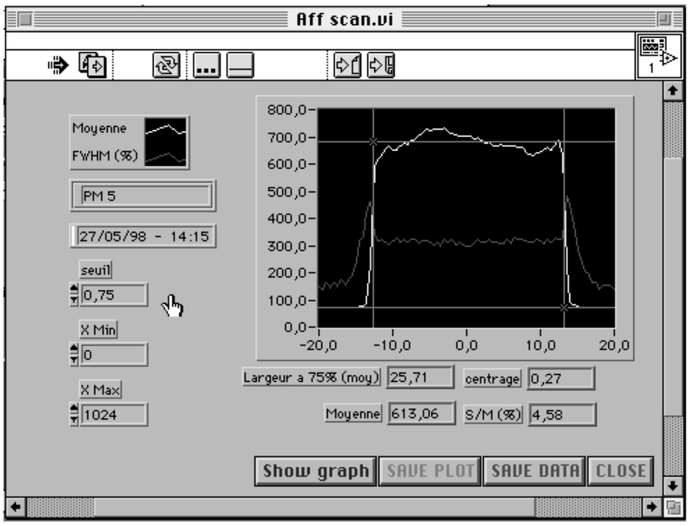

Fig. 3. Display of the results of the scan.

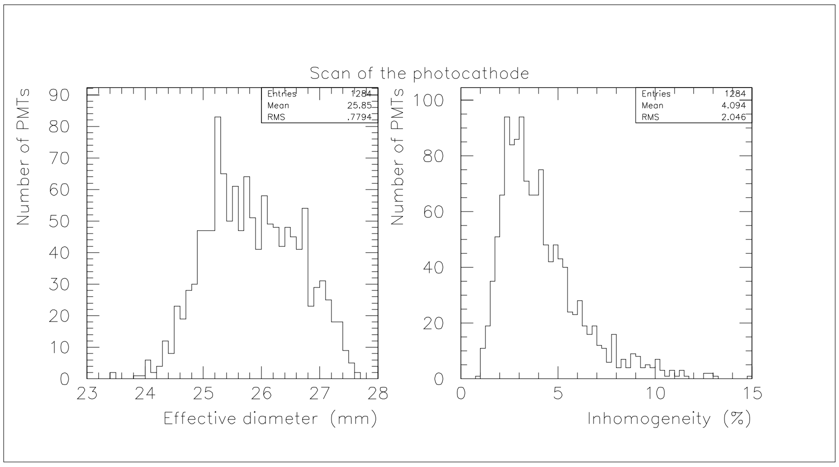

Fig. 4. Distributions of the useful diameter (left) and inhomogeneity (right) of the photocathode for all tested phototubes.

3 Effect of a magnetic field

A magnetic field is created around the PMT by two Helmholtz coils with a diameter of 30 cm [9]. Its intensity may be increased up to 20 Gauss and is measured by a Hall effect magnetometer with an accuracy of 0.2 Gauss. The phototube is still illuminated by a pulsed blue light, whose intensity is chosen to work in single p.e. detection mode. The measurements are performed using the operating conditions in the DIRC. The single p.e. signal is set at 20 mV and the electronic threshold at 3 mV.

The relative detection efficiency of the phototube is defined as the number of counts above threshold and in time with the pulsed light, normalised to 1 by the same number in a null magnetic field. Figure 5a shows the relative detection efficiencies of the PMT in magnetic fields of varying intensity with three different orientations with respect to the PMT axis, transverse and across the dynodes (X), transverse and along the dynodes (Y) and longitudinal (Z).

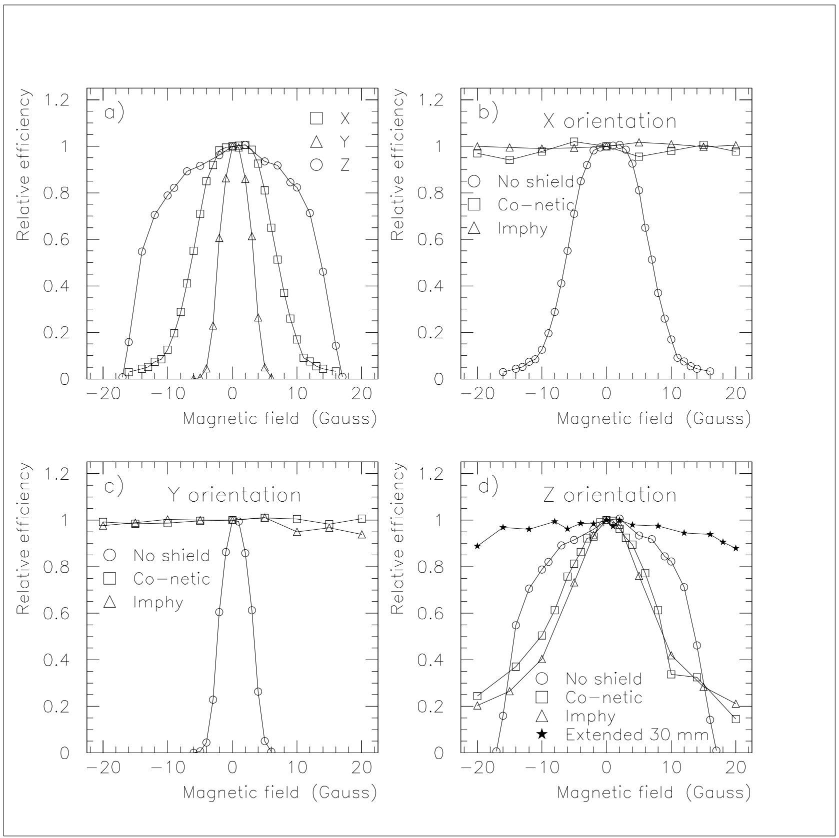

Fig. 5. Relative efficiencies of the PMT as a function of the magnetic field : effect of orientations (a) and of shielding in orientations X (b), Y (c) and Z (d).

Orientation Y is found to be the worst orientation. Furthermore the performance of the phototube is less degraded in a longitudinal field than in a transverse field. This is in agreement with measurements from the manufacturer. If we consider a random transverse orientation, we find a detection efficiency lying in between those observed for orientations X and Y. In fact, there is not much difference in the detection efficiencies obtained with a magnetic field oriented along either X or Z if the intensity of the field is smaller than 3 Gauss. But in the latter case, the detection efficiency decreases more slowly with the magnetic field for higher intensity. In a more quantitative way, the relative detection efficiency remains higher than 95% for magnetic fields up to about 1, 3 and 3.5 Gauss in the Y, X and Z directions respectively. It is still at 90% at 7 Gauss for axial fields, while it no longer exceeds this value beyond 4 Gauss in the X direction and 1.5 Gauss in the Y direction.

The magnetic field deteriorates the performance of the PMTs in two ways :

- decrease the efficiency of p.e. collection. A part of the p.e. created at the photocathode are deviated from their normal trajectories by the magnetic field and do not reach the first dynode.

- perturbate the electron multiplication. The magnetic field also deviates secondary electrons going from one dynode to the next one. A fraction of them are lost, causing a drop of the photomultiplier gain.

Figure 6a shows that the loss of efficiency is mainly due to a worse p.e. collection in the favorable orientation (X) and to a drop of the gain in the unfavorable orientation (Y) [10]. This effect is due to the geometry of the dynodes, sketched on figure 6b. A magnetic field oriented along Y deviates the electrons along the smaller size of the dynodes, which is precisely matched to the size of the multiplication shower. The effect of the magnetic field on the time transit in the PMT is represented on figure 6c.

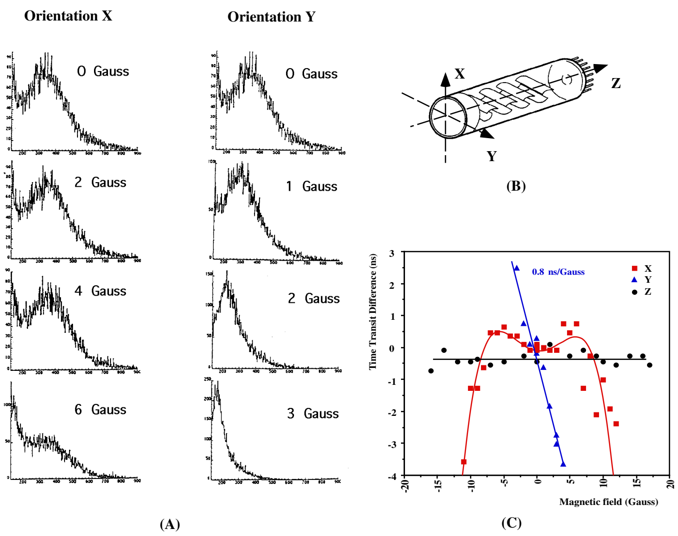

Fig. 6. ADC spectra for increasing intensities of the magnetic field in both transverse orientations X (left) and Y (right) (a), geometry of the dynodes (b) and effect on the time transit (c).

A well-known solution to minimise the effect of magnetic fields is to put the phototubes inside individual mu-metal shields. Two kinds of mu-metal called respectively Co-netic and Imphy were investigated. The former is manufactured by Perfection Mica Company (Illinois), the latter by Imphy S.A. (France). The only difference we noticed was the price in favor of Imphy. Both products appear as a metallic foil that is rolled around the PMT. They do not need rebaking after rolling. Several thicknesses were tried. A 0.1 mm thick foil was found to be sufficient. Figures 5b, 5c and 5d show the relative efficiencies of the PMT with and without the shield when the magnetic field is increased up to 20 Gauss. The two shielding materials, Co-netic and Imphy, give approximatively the same results. The performance of the shields is quite impressive for transverse fields with no need to extend the protection beyond the front end window. The efficiency of the PMT remains practically unchanged even in a transverse magnetic field of 20 Gauss, for both X and Y orientations. However for longitudinal fields, we observe a loss of efficiency when introducing the shielding ! The lines of magnetic field are disturbed by the presence of the shield and as a result a transverse field is created near the photocathode.

The solution to this problem is known. We have to extend the shielding beyond the front window of the phototube. When it is extendeded to 30 mm beyond, the PMT become nearly insensitive to longitudinal magnetic fields up to 16 Gauss. Its relative efficiency exceeds 95% over that range, as shown on figure 5d in the case of Imphy. The same result is obtained using Co-netic. However this solution is unfortunately not possible for the DIRC. Shielding the phototubes beyond the photocathode would indeed prevent us from installing light catchers in the inactive areas between PMTs and also introduce some shadowing effect, resulting in a loss of photon detection efficiency.

4 Effect of helium

We want to estimate which quantity of helium the DIRC phototubes can sustain. These PMTs will in fact stay for about 10 years in an environment subject to helium leakages. The pressure of helium P inside a phototube placed in a constant atmosphere with a partial pressure of helium P_0 will gradually increase with the time t from 0 to P_0. It can be parametrized, as shown in [11], as $\frac{P}{P_0} = \frac{t}{\tau}$, where the time constant τ depends on the composition and width of the PMT glass and on the temperature and total pressure outside the phototube. For the PMTs of the DIRC, $\tau \simeq 1.9 \times 10^{10}$ s $\simeq 590$ years. The above formula is only valid for $P < P_0$. For $P \sim P_0$, the dependence is no longer linear due to saturation. Helium is present in the air at a partial pressure of 0.53 Pa ($5.2 \times 10^{-6} P_{atm}$, where P_{atm} is the atmospheric pressure). Therefore with no extra source of helium, it will take nearly 600 years for the pressure of helium inside the PMT to reach this value, which is said not to be dangerous for the PMT [11]. To reach this value within 10 years, we need an average partial pressure of helium over 10 years of about 31 Pa ($3.1 \times 10^{-4} P_{atm}$), which is about 60 times greater than normal. To obtain the same result, we can also put the PMT in pure helium for about one day (27 hours). According to the manufacturer's statement, this should not damage the PMT.

To check this experimentally, the evolution of eight phototubes was studied over a period going from 2 weeks to 14 months [12]. The first two phototubes were measured in a mixture of helium and air for 15 days. The third one was studied in pure helium for 32 days. The next four PMTs have stayed in pure helium for 1, 3, 5 and 12 days respectively. They were then left in the air, where we have studied their evolution for 7 months. The last one was our reference PMT. It was kept away from helium and was measured over 14 months. We did not use the same experimental setup for all the phototubes. The first two phototubes, with their bases, were put entirely in the gas container filled with a mixture contisting of 90% of helium and 10% of air, as there were short circuits arcing at the PMT base in pure helium when putting the high voltage on. (The base is more sensitive to pure helium than the PMT !) Then in order to measure the third phototube in pure helium, we kept its base out of the helium container. Finally, the next four phototubes have been left, power off, in a small container filled with pure helium. We measured them before and resumed the measurement after we removed them from helium.

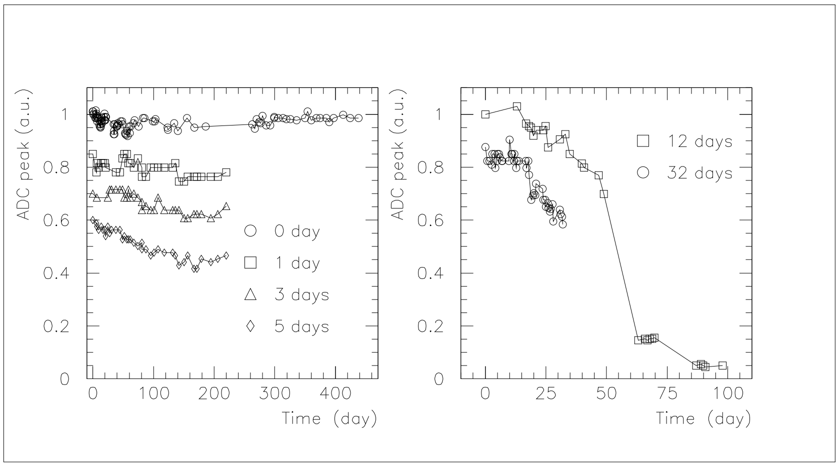

Fig. 7. Evolution of the PMT gain with time.

We essentially looked at the position of the peak corresponding to the single p.e. in the charge distribution measured in the ADC after pedestal subtraction, which is the most sensitive variable. This quantity is directly related to the gain of the PMT. The evolution of dark noise of the PMT was also measured, but no significant effect was observed with a threshold at 3 mV. Figure 7 shows the evolution of the position of the ADC peak, measured in arbitrary units, for the six last PMTs. The gain of the reference PMT is quite constant, as expected. The evolution of the first two phototubes, studied only during 15 days, is not shown on the figure, because their gain also remains constant. We did not wait long enough to see an effect. Indeed the gain of the phototube, kept in pure helium during 32 days, remained stable during nearly 20 days, then decreased. So it takes approximatively 20 days for helium to migrate through the PMT glass in sufficient quantity to affect the performance of the PMT. The borosilicate glass, recommended to us by ETL, as the PMTs will stay in pure water for many years, is quite resistant to helium leakages.

The fact that the gain of the phototube which stayed 12 days in pure helium is not affected after these 12 days confirms this result. It only begins to decrease significantly after about 25 days. Thus the helium, which has entered the glass, continues to move inside, when the phototube is in the air. Indeed it is repelled from the outside by the atmospheric pressure and not from the inside by the vacuum. After 50 days, the PMT gain has become very low, less than 20% of its initial value. Therefore a long stay in helium eventually destroys the PMT. After 7 months, we observe respectively a very small effect, a 10% and a 25% drop in the gain for the phototube which stayed 1, 3 and 5 days in pure helium. The gain seems to have reached a stable value, probably when all the helium in the glass has entered the PMT. In summary, 12 days in pure helium are enough to kill the PMT, 5 days produce a non negligible degradation, while 1 day seems to has nearly no effect, as anticipated in our previous calculation.

5 Conclusion

The basic characteristics of the ETL 9125FLB17 PMT used in the DIRC of *BaBar* are given : working high voltage, peak-to-valley ratio, timing resolution, dark noise rate and diameter of active area. The quality of the phototubes we have received meets the needs for the physics. The manufacturer has been able to correct some small problems, noticed during our quality control tests.

The performance of the PMT in a magnetic field depends sensitively on the orientation of the field. A longitudinal field is the least troublesome. There is a big difference between the two transverse orientations. The PMT can sustain a field of 3 (1) Gauss in the more (less) favorable transverse orientation if we accept a loss of efficiency of 5%. When mounting the PMTs on the detector, we took advantage of the degree of freedom of rotation, to orient the PMTs transversely so that the worst direction is in the calculated lower field component, which to first order is azimuthal with respect to the solenoid axis.

Although individual mu-metal shields provide a very good protection against transverse magnetic fields, they produce a non negligible degradation for longitudinal magnetic fields if the shield does not extend beyond the photocathode. As this option is not possible in the DIRC and the fringe field has a big longitudinal component, individual mu-metal shields cannot be used here. However it does not seem necessary. In fact, a magnetic shield of soft iron around the whole region of the PMTs and a tunable bucking coil allows a considerable reduction of the magnetic field at the PMTs to values smaller than 1 Gauss. The measured values of the magnetic field on site are in good agreement with the anticipated ones [6]. Consequently, we should not experience problems due to the magnetic field. Magnetic probes [13] with a range of 10 Gauss and a resolution of about 0.1 Gauss will allow the monitoring of the intensity of the magnetic field near the PMTs during data taking.

The effect of helium leakage has also been quantified. The PMTs are quite resistant, being able to stay in pure helium for a few days with little damage. The worst danger would be a helium leakage while the detector is open. In this case, big fans can be used to blow the helium away from the PMTs.

Acknowledgements

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