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Characterization of 900 four-anode photomultiplier tubes for use in 2013 hadronic forward calorimeter upgrade

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CHARACTERIZATION OF 900 FOUR-ANODE PHOTOMULTIPLIER TUBES FOR USE IN 2013 HADRONIC FORWARD CALORIMETER UPGRADE

by

Emrah Tiras

A thesis submitted in partial fulfillment
of the requirements for the Master of
Science degree in Physics
in the Graduate College of
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Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Emrah Tiras

has been approved by the Examining Committee
for the thesis requirement for the Master of Science
degree in Physics at the July 2012 graduation.

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Edwin Norbeck

To my wife, Kevser, and family
Their endless love gave me forces to make this possible.

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ABSTRACT

The first 900 four-anode Photomultiplier Tubes (PMTs) have been evaluated for use in the 2013 Hadronic Forward (HF) calorimeter upgrade. HF is a part of the Compact Muon Solenoid (CMS), which is one of the two large general-purpose particle detectors of the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland. HF requires 1728 PMTs. These small tubes are the sensitive light detectors that provide the output signals of HF. Before installing PMTs in HF, their quality control demands need to be satisfied. These tests, done at the University of Iowa, are designed in three categories to test seventeen different parameters for each PMT. The three most basic and most important groups of parameters are: dark current, gain (anode and cathode), and timing. There are secondary tests which are performed on a smaller percentage of the PMTs such as surface uniformity, double pulse and single photo-electron resolution. The PMTs that meet the specifications of HF will be sent to CERN where they are expected to be in use for at least a decade.

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CHAPTER 1

INTRODUCTION

Photomultiplier Tubes (PMTs) are sensitive light detectors that are commonly used in high energy physics experiments. These small tubes play a crucial role in many of the detectors in the Compact Muon Solenoid (CMS), which is a large detector used with the Large Hadron Collider (LHC) at CERN. PMTs are located in the rear of Hadronic Forward calorimeter (HF), one of the sub-detectors of CMS, to determine the tracks, energy and momentum of the secondary particles (jets) produced from the collisions. With the LHC upgrade scheduled for 2013 the LHC will reach an energy of 14 TeV with high instantaneous luminosity. This will require new specialized high quality PMTs for use in HF. A new four-anode PMT from Hamamatsu has been chosen to upgrade HF for the larger energy and luminosity starting in 2013. Because they are expected to be used for at least a decade, their specifications need to be checked by using quality control techniques and methods before embedding them into the real experimental setup. The Experimental High Energy Physics (HEP) group at the University of Iowa is responsible for testing 1800 new four-anode PMTs for the 2013 HF upgrade. The HEP group improved the experimental setups for these new quality control measurements, from the earlier tests Iowa conducted on the original 2000 PMTs [1] currently installed in HF.

The traits of each PMT were characterized in separate tests. These quality control measurements are crucial because testing PMTs before installation enable us to realize and solve any possible problems during the operation. The results also guide us to consummately install PMTs in the calorimeter. In this study, the testing procedure is briefly explained, and the results of the selected tests performed on 900 PMTs are presented.

PMTs are generally used to measure the light from secondary processes. One of these secondary processes results in what is known as "Cherenkov radiation" being produced. Cherenkov radiation is light produced when charged particles travel in a medium faster than the speed of light in that medium [2]. Since the speed of light in the medium depends on the index of refraction of this medium, (given by $c_{medium=}$ c/n), where "c" is the speed of light in vacuum); the speed of light in a medium such as glass (n=1.5), is slower than the speed of light in air (n=1), for example. A charged particle entering this same medium is not affected by the index of refraction of the medium, so it can travel faster than light in that medium, resulting in Cherenkov radiation being emitted. This is the radiation that the experiments are trying to measure.

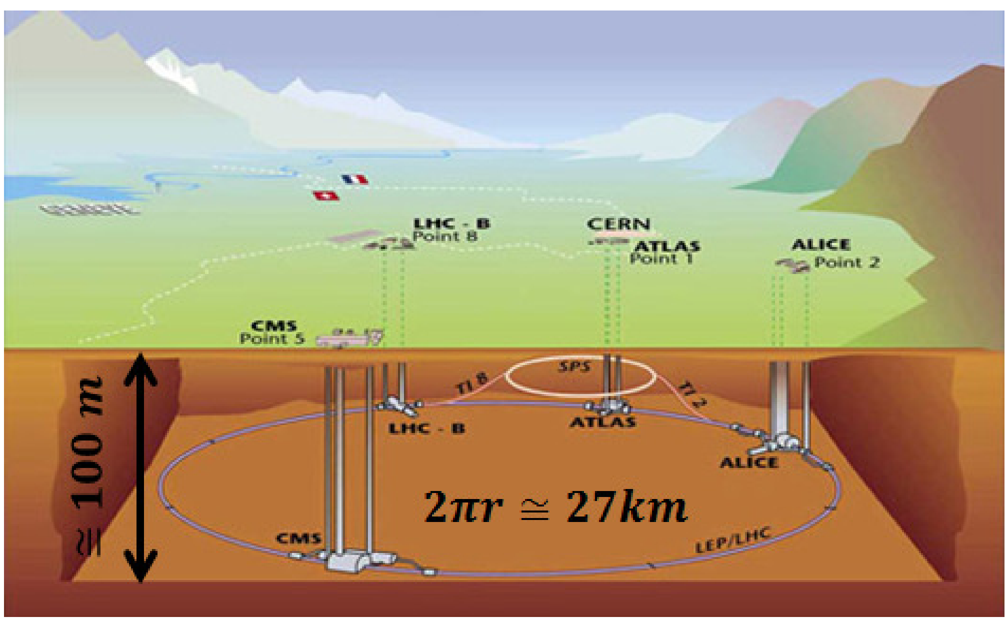

Figure 1.1: The overall view of the LHC at CERN and four main experiments at LHC: CMS, ATLAS, ALICE, and LHC-B.

CERN is the French acronym of Conseil Européen pour la Recherche Nucléaire which means European Council for Nuclear Research. CERN is located in Geneva, Switzerland and hosts the largest and highest energy particle accelerator [3], the Large Hadron Collider (LHC), which is twenty-seven kilometers in circumference and about one hundred meters under the ground, see Fig. 1.1. The LHC enables scientists to collide two groups of particles such as protons and lead ions. This gigantic particle collider is located at the border of Switzerland and France and physicists from all over the world analyze and study the new particles that are created in these collisions.

As can be seen in Fig. 1.1 the LHC has four main experiments and each consisting of a large array of detectors. These are CMS, ATLAS, ALICE and LHC-B. Each experiment is designed for different purposes. For instance, CMS is designed to measure the energies of particles such as hadrons, gammas, leptons and jets produced by proton-proton collisions at very high energies [4].

There is an HF mounted at each end of the CMS detector. The purpose of these calorimeters is to improve the measurement of the missing transverse energy and identify ‘jet’ energies; jets are created when quarks and gluons produced during the collisions decay into hadrons like protons, neutrons, kaons and pions as they move away from the collision point. The CMS and HF are explained further in Chapter 2.

Thousands of scientists and engineers from hundreds of institutions collaborate in each experiment with the main goal of a better understanding of the material world and for advancing technology. For example, the total number of participants in CMS is 4300 [5]. The University of Iowa is one of these institutions and actively participates in the CMS collaboration by hosting a lot of scientists [6] who are improving detectors, hardware for the experiment and analyzing data to find new physics in the particle world.

CHAPTER 2

THE COMPACT MUON SOLENOID (CMS) EXPERIMENT AND THE HADRONIC FORWARD CALORIMETER (HF)

The Compact Muon Solenoid (CMS) is one of the two large general-purpose particle detectors of the Large Hadron Collider (LHC) project at European Particle Physics Laboratory, CERN. As can be seen in Fig. 2.1, Hadronic Forward (HF), Hadronic Barrel (HB) and Hadronic Endcap (HE) constitute the hadronic calorimeters [7] of the CMS experiment.

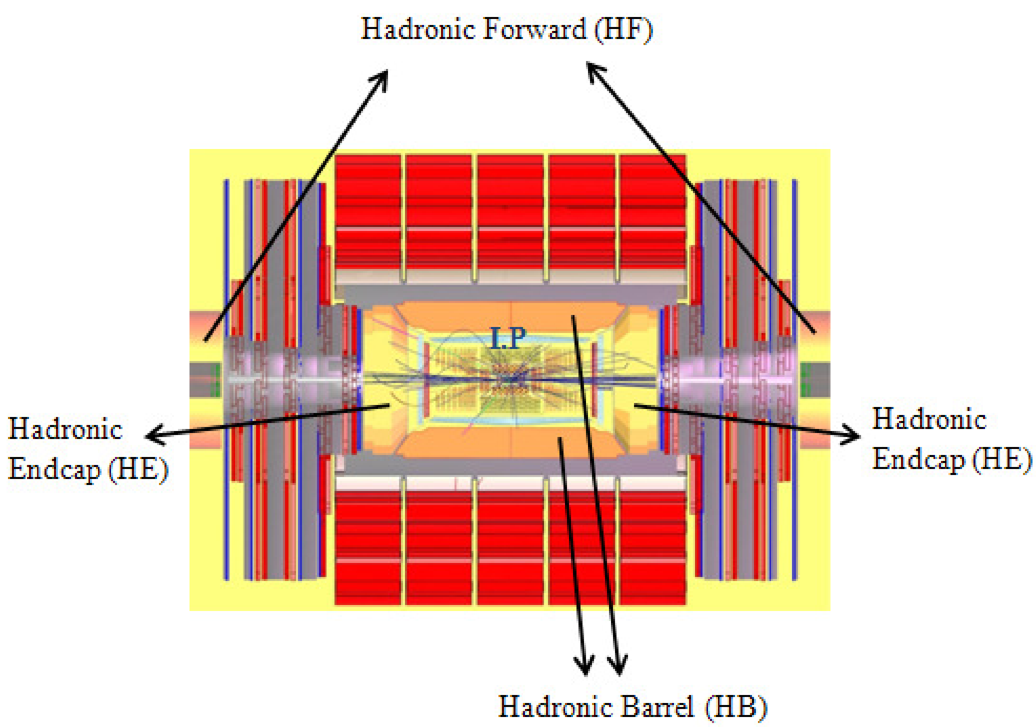

Figure 2.1: Three main sub-detectors of CMS: Hadronic Forward (HF), Hadronic Barrel (HB) and Hadronic Endcap (HE).

Each sub-detector of the CMS carries different purposes in the experiment. There are two purposes served by the HFs. The first purpose is to enhance the measurement of the missing transverse energy E_T^{mis} in the experiment. The second purpose is to identify high energy jets from the collisions. Because jets play a crucial role for understanding both Higgs production and SUSY particles, identification and reconstruction of these jets are key signals of new physics.

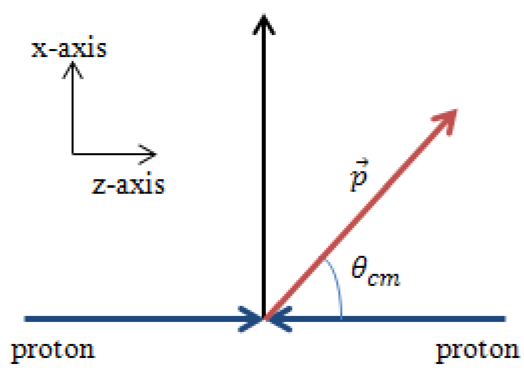

Figure 2.2: Pseudorapidity angle and the interaction point of the collision.

There are two identical Hadronic Forward (HF) calorimeters, one at each end of the CMS. These are HF- and HF+, located at about $\mp$11m from the interaction point (I.P). Both of them are in the pseudorapidity range $3.0 < |\eta| < 5.0$. As shown in Fig. 2.2, the pseudorapidity(η) is related to the angle of a particle relative the beam axis and is given by;

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \tag{2.1}$$

In Eq. 2.1 θ_{cm} is the center of mass scattering angle (polar angle) between the particle's momentum ($\vec{p}$) and the beam axis (z-axis). The polar angle range represented by the pseudorapidity range ($3.0 < |\eta| < 5.0$) is $0.78^{\circ} < \theta_{cm} < 5.70^{\circ}$.

Since the LHC is designed for the highest energy ever ($\cong 14\, TeV$) and high luminosity ($\cong 10^{34} cm^{-2} sec^{-1}$), that is the number of particles per unit area and per unit time times the opacity of the object, the expected radiation is about $100\ Mrad$ per year and $1\ Grad$ in 10 years, operation time at the pseudo-rapidity $\eta = 5$ [7]. Hence, the HF modules must be radiation hard to survive that much radiation. For this purpose, HF modules were constructed from steel blocks with embedded quartz fibers [8]. The fibers are parallel to the beam axis. These steel blocks can be seen in Fig. 2.3. The fiber used for the each HF module is approximately 1000 km in length.

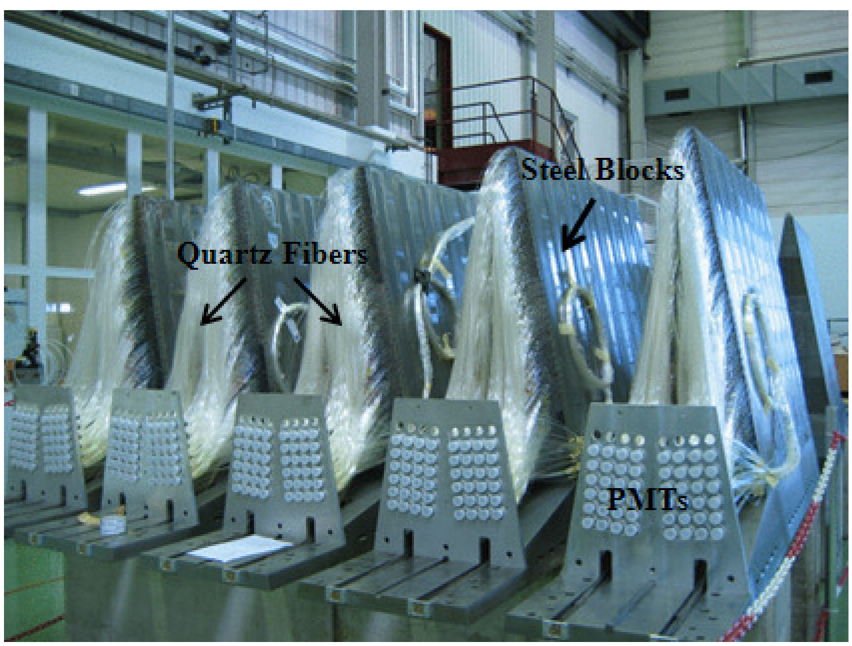

Figure 2.3: HF wedges: Quartz fibers coming off the absorber steel blocks before installation into the CMS cavern.

HF is constructed with two different types of fibers: long (L), and short (S) length fibers, and they are about 165 cm and 143 cm respectively. The long fibers run along the entire length of the absorber, and the short ones stop 22 cm from the front face of the absorber. The short fibers are not sensitive to the EM showers, but the long fibers are sensitive to both EM and hadronic showers. The fiber bundles coming off from the back of the absorber are connected to the PMTs which are fixed in between the cylindrical protective block and the outer layer of the detector at the back of the HF ($100cm < r < 140cm$). In this region, the radiation from all the sources, expose to the PMT is less than 10 $krad$ per year [7]. Also, the magnetic field is only a few hundred gauss while the magnetic field in the center of CMS is 38,000 gauss. A low radiation area is crucial for PMTs.

The HF has a cylindrical shape with the inner radius and outer radius being about 12.5 cm and 130 cm, respectively. The length of the calorimeter is about 165 cm. In Fig. 2.4 the HF front face is shown with the tower structure that is of a square geometry in which PMTs are located. There are 432 towers in each HF module that is divided into 36 segments in azimuth (φ) and 12 segments in pseudorapidity (η). These towers have different triangular shapes and sizes. Each tower has short and long fibers so each tower is read by two PMTs one for the short fibers and one for the long fibers.

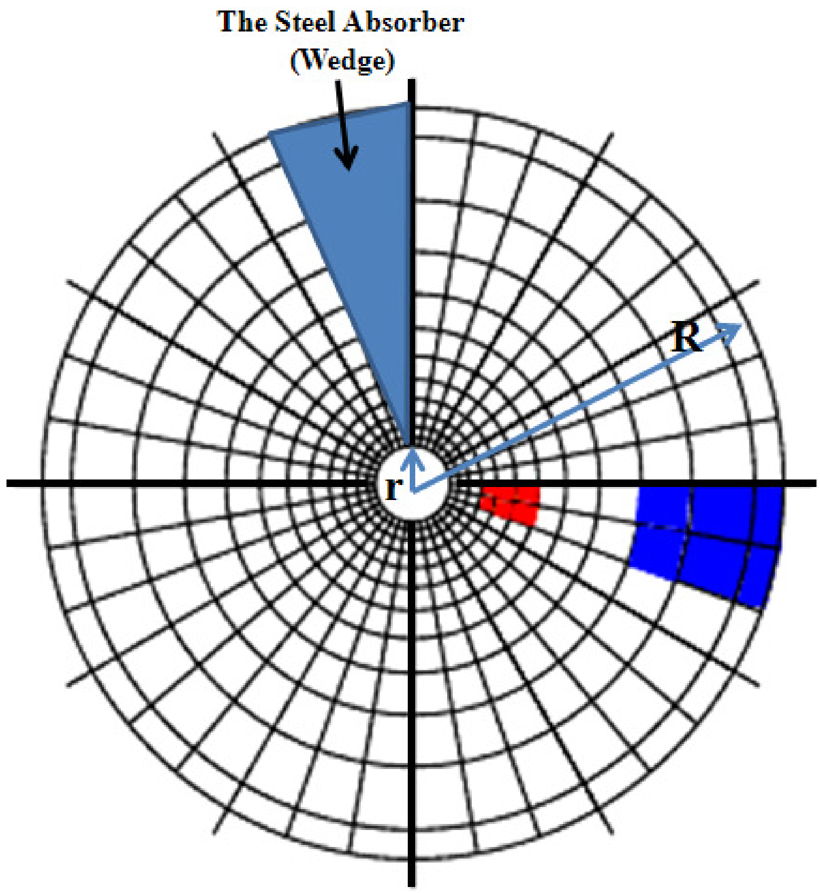

Figure 2.4: The HF front face with the tower structure with the inner radius (r) and outer radius (R) and PMT locations are described in the text.

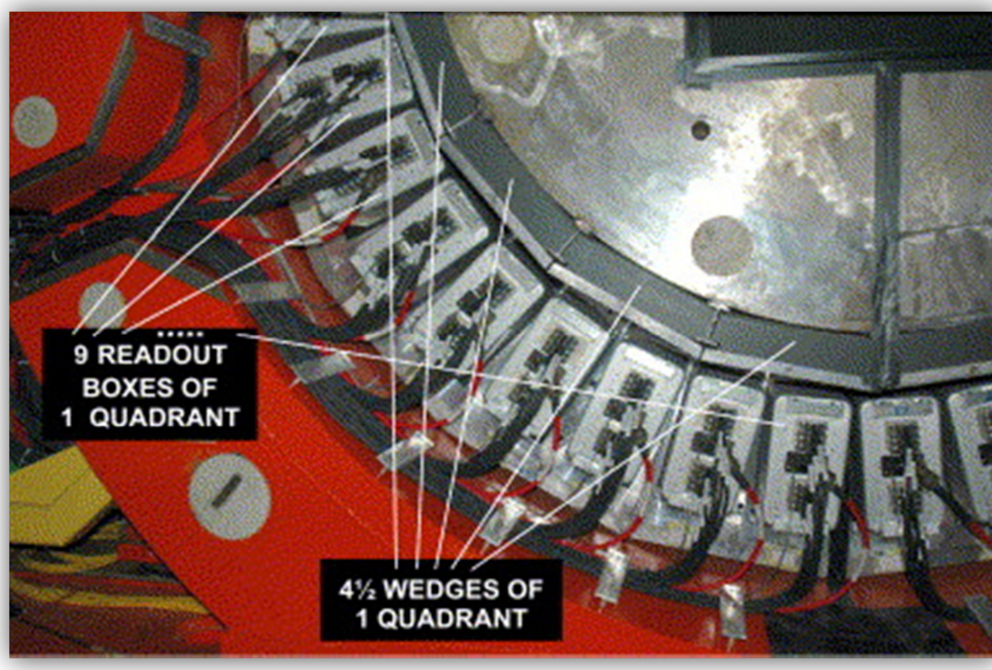

Figure 2.5: In each quadrants of the HF, total 216 PMTs are located equally in 9 identical readout boxes, with 24 PMTs in each box [9].

The HF calorimeters are built in four quadrants. Each HF calorimeter consists 18 steel absorber modules (wedges). Each wedge has two readout boxes and each box has 24 PMTs in it. As shown in Fig.[1] 2.5, each quadrant has 216 PMTs inside the 9 PMT readout boxes. There are 864 PMTs used in each HF calorimeter for a total of 1728 PMTs. All the readout boxes are identical. Between the boxes and fiber bundles, there is a steel plate which holds all the fiber bundles and hosts the light guides through which the light goes from the fibers to the PMTs.

[1] This figure was taken here from (N. Akchurin *et al.,* 2005)

2.1 Operating Characteristics of Photomultiplier Tubes

Photomultiplier Tubes (PMTs) are extremely sensitive electron tube devices that convert a photon signal to an electrical signal. A schematic diagram[2] of a PMT is shown in Fig. 2.6.

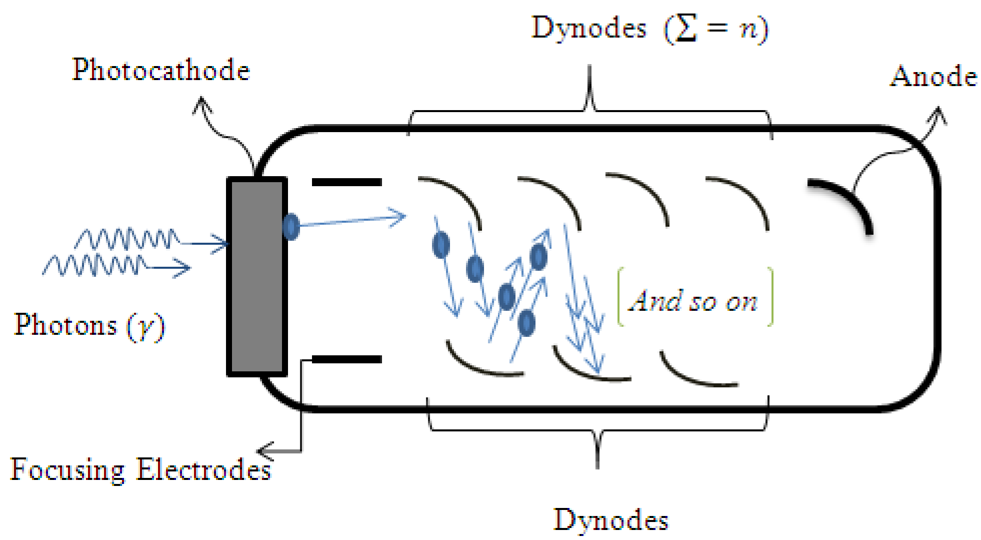

Figure 2.6: Schematic diagram of a linear focused type PMT and the total number of dynode structures ($\sum dynodes = n$).

A typical PMT consists of a photosensitive material (photocathode) followed by focusing electrodes, an electron multiplier section (dynodes), and anode (collector) in an evacuated tube. When light impinges upon the photosensitive material's surface, electrons are emitted into the vacuum by the photocathode via the photoelectric effect which is explained below. These electrons called photoelectrons are directed and accelerated toward the first electron multiplier (dynode) with the help of the applied high

[2] The dynode chains in Figure 3.1 is arranged in a linear focused type as an example but the PMTs are used for the 2013 HF upgrade have dynode chains in a circular cage type. However, they have the same operational characteristics.

voltage. When these photoelectrons hit the first dynode, the secondary emission occurs and the numbers of the electrons are multiplied. Then, these multiplied electrons are directed to the second dynode, and then more and more electrons are released and accelerated toward to the third dynode. The multiplication process is repeated over all the dynode stages. As the final step, the anode collects all these multiplied electrons and provides an output signal that can be amplified and analyzed.

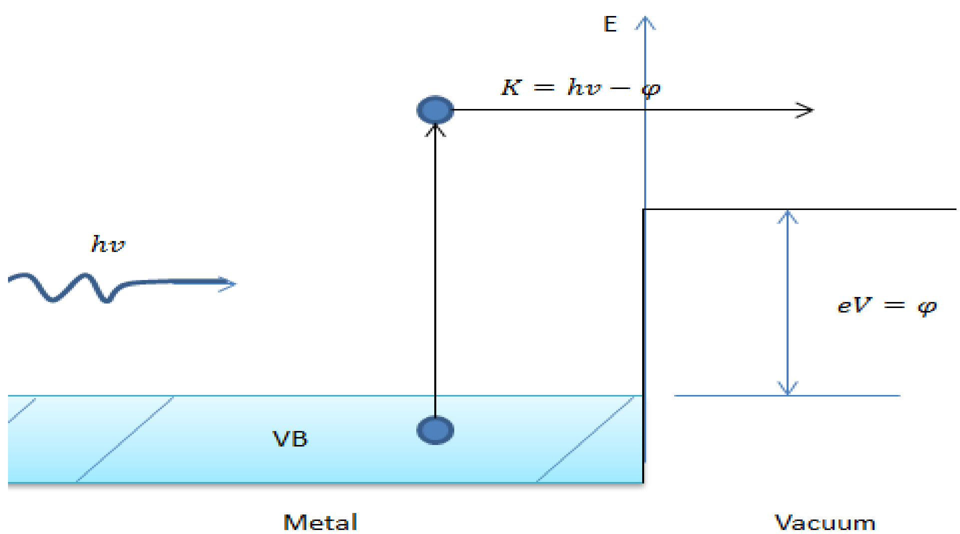

Figure 2.7: The energy level diagram of a metal and the photoelectric effect

Fig. 2.7 shows the kinematics of the photoelectric effect. The electrons are bound to the metal with energies ≥ eV= φ (work function). When a photon of energy hυ hits the metal, electrons are emitted with the kinetic energies K ≤ hυ-eV(φ).

2.2 The CMS-HF PMT Test Station at the University of Iowa

The University of Iowa CMS-HF PMT Test Station was designed to measure all 17 different PMT quantities mentioned in Chapter 3. There are three dark boxes designed to be light tight and each of them houses several setups. The first box (α) houses the setups used for dark current, relative gain, and anode and cathode gain. The single photoelectron resolution measurements and all timing tests are tested in the second dark box (β). We perform the surface non-uniformity test in the last dark box (γ).

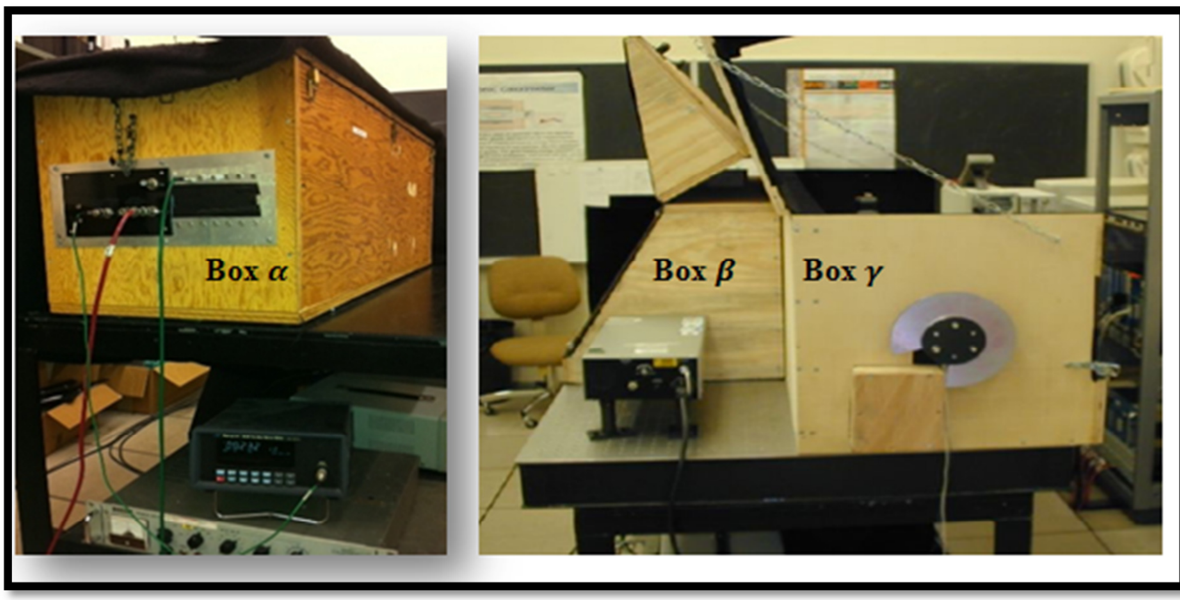

Figure 2.8: Light Tight Boxes: α, β and γ are aimed to use for measuring different parameters.

The three light tight boxes are shown in Fig. 2.8. A patch panel is located on one side of each dark box for the purpose of signal and high-voltage cable connections. We use equipment such as a Tektronix oscilloscope, a GPIB-USB cable, pico-ammeters, digital scope, ultra-violet (UV) and visible power meters, UV and blue light sources, two nitrogen lasers, one nitrogen dye laser, tungsten light bulbs, optical tables with all mounts and stands, VME and CAMAC data acquisition systems, one double pulse generator, and a computer controlled XY scanner, which allows us to move a pin sized light source in two dimensions across the surface of a PMT.

2.3 The Previous R&D Studies and Tests for HF Upgrade

The provided candidate PMTs from manufacturers, Hamamatsu, Photonis and EMI-Electron Tube, were evaluated at the University of Iowa CMS-HF test station in 2003 [10]. The parameters; gain, timing, dark current, linearity and single photoelectron resolution were measured for the each PMT from the companies. Because the Hamamatsu R7525HA PMT satisfied perfectly the specifications by CMS-HF, the PMTs from the Hamamatsu Company were chosen.

2000 PMTs were embedded into the HF calorimeters to read out Cherenkov light from quartz fibers. For this purpose, 2000 PMTs were characterized at the test station at the University of Iowa in 2003 [1]. The HEP group at the University of Iowa categorized the tests into two sets. In the first set, they tested each PMT for timing response, dark current and relative gain. In the second set, they tested some of the PMTs for single photoelectron resolution, spatial uniformity, and gain verses high voltage measurement. Twenty PMTs were rejected because they had too much dark current. Overall, the 99% of PMTs showed good agreement with the requirements of HF.

2.4 The CMS-HF Requirements for the 2013 HF Upgrade

In the previous tests the PMTs from the Hamamatsu Company were chosen because of their agreement with the previous specifications of HF [10]. For the 2013 HF upgrade a new type of four anode metal package R7600U-100-M4 photomultiplier tubes from Hamamatsu (see in Fig. 2.9) were chosen by the CMS-HF academic advisory board to use in CMS.

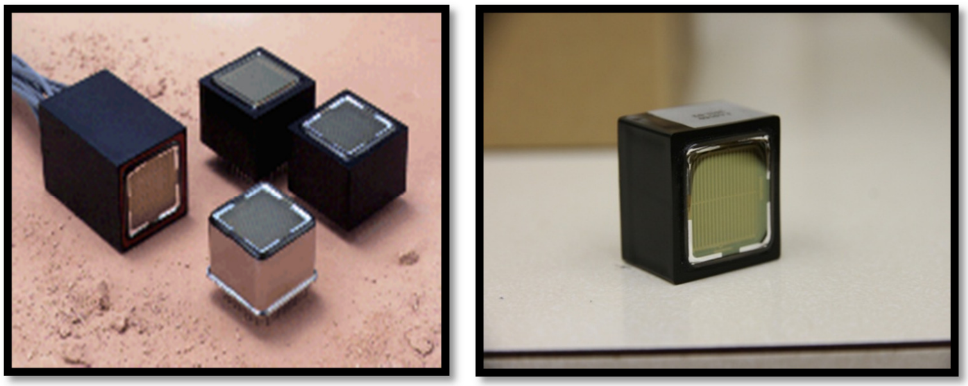

Figure 2.9: R7600U-100-M4 type metal package Photomultiplier Tubes from Hamamatsu

CMS has quality requirements for each PMT due to the operation and mechanical design of HF. A summary of the HF-PMT requirements is listed in Table 2.1.

Table 2.1: CMS-HF Requirements for Photomultiplier Tubes in 2013 HF calorimeter R&D and upgrade studies

Summary of the HF-PMT Specifications[3]	
Window Material	: Borosilicate glass
Window Thickness	: 0.8mm, 0.1mm
PMT Envelope	: Metal envelope except window, seals to electrodes
Photocathode Type	: Bi-alkali or equivalent
Quantum Efficiency	: 38% min. at 400 nm
Cathode Luminous Sensitivity	: > 135 µA / lm

[3] This list was updated by CMS on September 24th, 2010.

Table 2.1 continued:

Cathode Radiant Sensitivity	: > 130 mA / W
Cathode Blue Sensitivity Index	: 15.5
Anode Luminous Sensitivity	: 175 A / lm min.
Anode Radiant Sensitivity	: 1.7 x 105 A/W min.
Maximum Size perpendicular to axis	: Within 31 mm square or less
Effective Photocathode Area	: 300-500 mm^2
2 x 2 Multi-anodes, Anode Size	: 9 mm x 9 mm / Anode
Quantum Efficiency	: >38% (350-500 nm)
Dynode Structure / Stage	: Metal Channel / 10, or equivalent
Gain	: 1 x 10^6 min.
Dark Current after 30 min. /anode	: 1 nA max per anode at applied voltage of 800 V
Rise Time	: 2 ns maximum at applied voltage of 800 V
Pulse Width	: 15 ns maximum at applied voltage of 800 V
Transit Time	: 25 ns maximum at applied voltage of 800 V
Applied Voltage	: 800 - 900 V
Anode Crosstalk	: 4% maximum with aperture size of 9×9 mm
Photocathode Lifetime	: 200 mC min.
Single Photoelectron Resolution	: 80% or better (rms/mean of SPE peak) per anode
Pulse Linearity	: Peak current of 10 mA min at ±2% deviation/anod.
Gain (1/2)-lifetime	: 1500 C min.
Operating Ambient Temperature	: -30 to +50 C degrees
Storage Temperature	: -30 to +50 C degrees
Gain Stability	: ±5% max within 12 hr. w. anode current of 100 μA
Anode Current vs. Position	: ±45% with 3 mm spot scans
Response Uniformity (Between Each Anode)	: 1:1.5 maximum

CHAPTER 3

PROCEDURE OF PMT TESTS AND EXPERIMENTAL SETUP

The successful operation of the HF Calorimeter is directly related to several factors such as the quality of PMTs, the intensity and wavelength of the incoming Cherenkov light and environmental conditions such as radiation, humidity and temperature. Therefore, the HF Calorimeter specifies operational requirements, which are listed in Section 2.4. The operational requirements are defined as criteria for each test's expected value for the PMT.

In the present study, the tests are designed in three categories in terms of specific requirements of HF. The first category is called "primary (complete)" category and the second and third category are together called as "secondary (batch)" category. These primary and secondary test sets will be briefly explained further down and selected important test parameters and their experimental setups will be described. Moreover, each PMT is inspected before performing any test on it. Any unexpected flaws such as cracks or scratches are noted. PMTs are ready for testing after this preliminary inspection.

3.1 Primary (Complete) PMT Tests

In the first category, ten different parameters are tested for each PMT. These parameters are: dark current, gain (anode and cathode), negative pulse width, rise time, transit time, transit time spread, single pulse linearity, cathode luminous sensitivity, anode luminous sensitivity, and cathode blue sensitivity measurements. Rise time, pulse width, transit time, and transit time spread are categorized in one set that is called timing. The four most important tests dark current, gain, timing, and linearity with percentage error are recorded and their results analyzed.

3.1.1 Dark Current

Dark current is a minuscule current produced by a photomultiplier tube when the lens is capped and no light is being measured. It is always there and we call this output current "background current". Dark current is caused by the noise or the background noise but should not be confused with the statistical noise. Statistical noise [11] is a shot noise caused directly by the photoemission or secondary emission processes and the rms deviation[4] is given by:

$$\Delta I^2 = \frac{I\, e}{\tau} \tag{3.1}$$

In Eq. 3.1, I is the cathode current, e is the electron charge and τ is the time period of the photons to reach the photocathode. This is for measurements of small steady light levels.

In most PMTs, the dark current is not more than a few nano-amperes. Even if it is around that small amount, the background current is a critical factor in determining the detectivity of a PMT. The most known sources of the dark current are:

- **Thermionic emission of electrons:** This is the principal source of the background noise. This happens because photocathodes and dynodes have low work functions and can emit electrons even at low temperatures. The Richardson's equation below shows this relation:

[4] This equation is the result of the assumptions: Poisson distribution for the total number of photons and the light pulse distribution probability for the total number of released electrons from the cathode surface.

$$I = AT^2 \exp\left(\frac{-\,e\,\varphi}{k\,T}\right) \tag{3.2}$$

In Eq. 3.2, A is a constant, T the temperature [K], φ is the work function and k Boltzmann's constant. As can be seen in this formula, if the PMT is operated at a lower temperature, the background noise is reduced.

- **Leakage currents:** Leakage currents caused by the supports; pins at the base as well as the glass stem base and socket, and it could increase the current.
- **Contamination:** Contamination on the surface of the tube can cause the background noise. This is the radioactive material contamination and it causes electron emission either from the cathode surface or dynodes.
- **Emitted electrons:** At high voltage values the electrons can be emitted by the strong electric field.
- **Ionization of remaining gases:** The electrons coming through the PMT can ionize the leftover gas in the PMT. This can cause a detectable current pulse.

The dark current is significantly dependent on the high voltage supply as can be seen in Fig. 3.1. In this sense, the dark current test checks the noise of the PMTs at different voltages without any light source. In this test, we determine whether or not the noise of the PMT is smaller than the signal that is being measured. If the noise is too great, the PMT cannot be used.

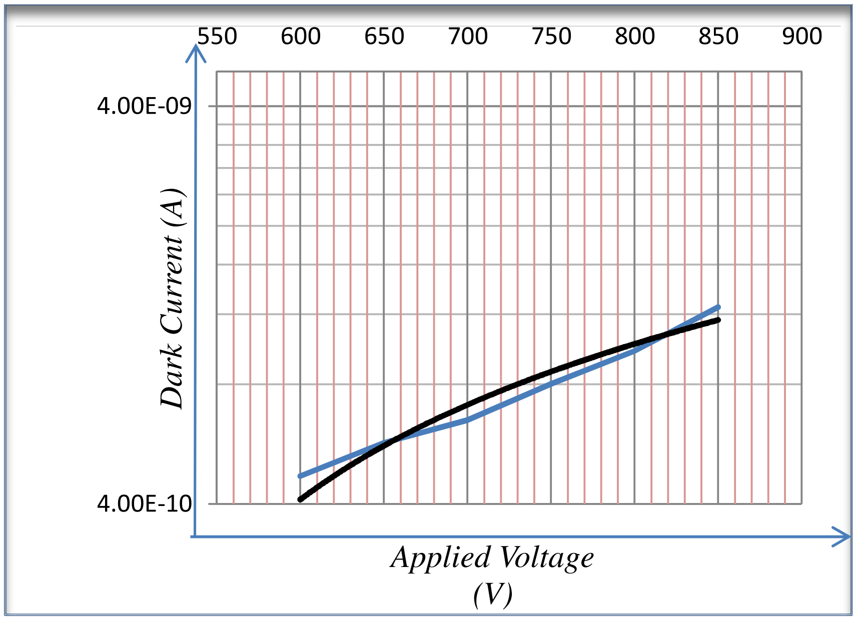

Figure 3.1: Dark Current vs. Supply Voltage for one PMT with serial number JA0883

The materials of the testing procedure consist of a PMT base, pico-ammeter, GPIB-USB cable, computer, and high voltage power supply. The pico-ammeter is connected to the computer with the GPIB-USB connection. To measure the noise of each PMT, we carefully plug each PMT in the baseboard and put it into the dark box. We hook up the signal cable to the box's through-connection and read the signal into the pico-ammeter. The data from the ammeter is then read into the computer using an Excel macro to save the data. This test is run from 600-900 volts in 50 volt increments. At each voltage 20 measurements are made and then the average of these is taken as the final data point.

3.1.2 Gain (Anode and Cathode)

The gain of a PMT is the ratio of the anode current to the cathode current, in other words, how much the PMT amplifies the incoming signal. The gain is defined by the equation (3.2):

$$G = \left(\frac{I_a}{I_c}\right)\left(\frac{Li_c}{Li_a}\right) \tag{3.3}$$

In Eq. 3.3, I_a is the anode current, I_c is the cathode current, Li_c is the cathode light intensity, and Li_a is the anode light intensity. The light intensity proportionality is included in this equation to account for differing light intensities during the course of the study. The gain increases with the voltage applied to it. With the gain test we measure the anode and cathode gap within the PMT in terms of current. As explained in Section.3, the multiplication process continues at the each dynode stage and a gain achieved as an output signal. Theoretically, the gain depends on the secondary emission factor (δ) and the number of dynode stages (n) and given by (3.4). The secondary emission factor is a simple energy function of the primary electron and given by $\delta = L \times V_d$. Here, V_d is the potential difference between the dynodes and L is the proportionality constant. Assuming there are some dynodes related to the number n (Fig. 2.6) inside a PMT and the voltage difference between each two dynodes are the same, the overall gain G is then:

$$G = \delta^n = (L \times V_d)^n \tag{3.4}$$

For the gain test setup, the materials of the testing procedure are the same as those with the dark current test, with extra materials consisting of a light source and a neutral density filter (NDF). NDF is a filter that modifies the intensity of wavelength and color of the light. This setup uses the same computer connection to the pico-ammeter using the GPIB-USB connector. The data is also read into an almost identical Excel sheet using the same macro. Differing from the dark current test, this test involves irradiating the PMTs with light. The PMT is placed at one end of the box and a light source and a diffuser are placed at the other. The gain test has two almost identical parts to it: the first portion of the test is the cathode measurement and the second part of the test is the anode measurement. The cathode test is the measurement of the current due only to the photocathode. This is done by placing the PMT in a baseboard which is placed in a holster (see in Fig. 3.2) and shining light on it. Because the cathode has no multiplicative properties, a higher level of light is used than on the anode. The cathode test uses a light intensity of ~13nW.

Similar to this, the anode test uses the same holder but different baseboard (see in Fig. 3.3) to irradiate the PMT with light. But due to the fact that the anode is post-multiplication, a much lower light intensity is used. The light intensity is decreased from the source using a neutral density filter. The light level is brought all the way down to ~.02nW. During each of the anode and cathode tests the different light intensities are recorded since they play a role in the final computation of gain. The current signal of the anode and cathode is recorded while the high voltage is increases from 600V to 900V in 50 volt increments. Once all of the quantities have been collected the final gain is found using the gain formula mentioned previously.

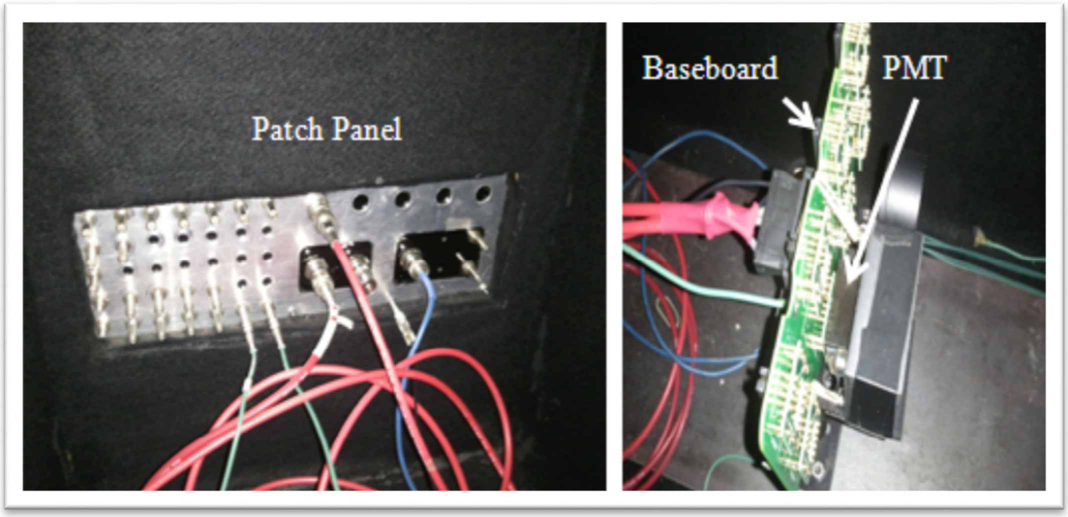

Figure 3.2: The patch panel of the Box-α and PMT baseboard for dark current and anode gain test.

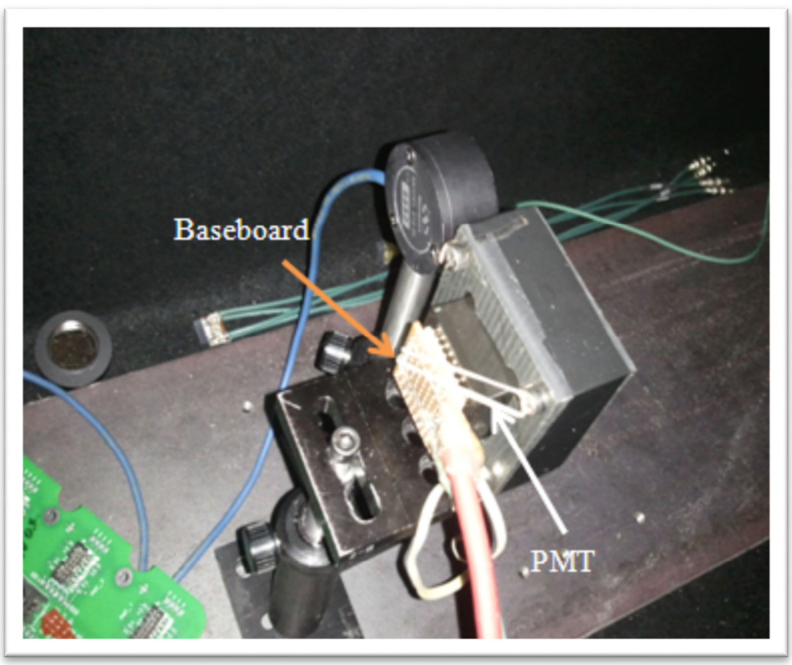

Figure 3.3: The baseboard and the PMT setup for cathode gain test.

3.1.3 Timing

The time response of the PMT plays a crucial role for the successful operation of the HF calorimeter because collisions occur 25 nanoseconds apart, which is very fast. The reading and recovery speeds of PMTs are observed in these tests. There are four quantities that are all determined with the same test and apparatus. These quantities are rise time, pulse width, transit time, and transit time spread. Transit time is the time interval for photoelectrons to travel from the cathode to the anode and it depends on the applied voltage (V) and dynode structure. There is some inevitable fluctuation in the transit time because of the different impact points on the photo-cathode. The transit time spread is the time variation in transit time occurred by fluctuations. Rise time is the time it takes for the signal to rise from 10% to 90% of its maximum amplitude. Finally, the pulse width is the full width at half maximum (FWHM) of the signal amplitude.

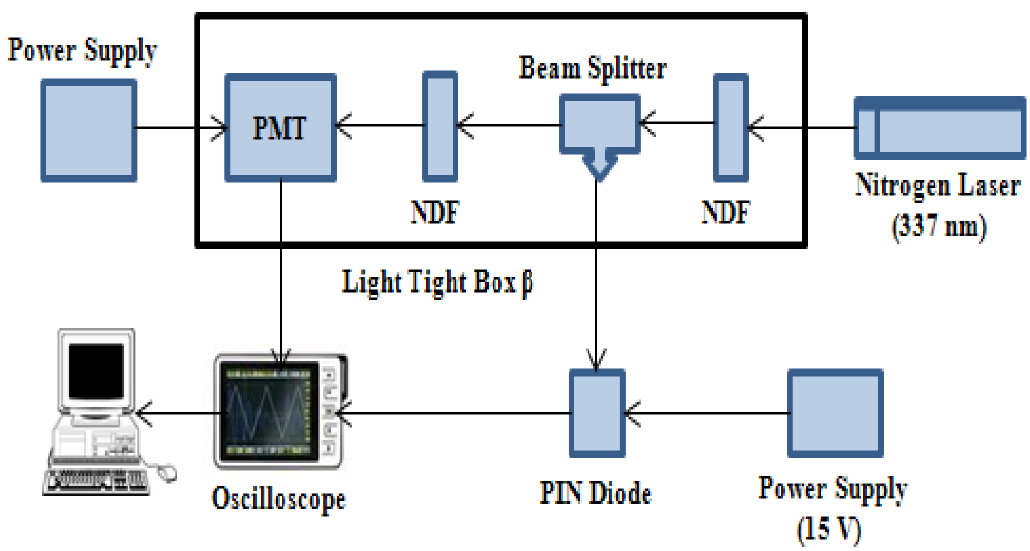

Figure 3.4: Schematic representation of the Box-β and the timing set-up.

The materials of the testing procedure are displayed in Fig. 3.4. The timing test is performed in a different dark box and is done using a pulsed laser. The PMT is placed at one end of the box in a base board with the signal run out of the box to an oscilloscope. At the end of the box there is a laser that is pointed at the PMT. The laser beam is split into two beams. The first beam is sent to a PIN diode which measures the signal of the laser and sent to the oscilloscope after being delayed according to the travel time of the light to the PMT. The second half of the split beam is passed through a neutral density filter and a diffuser and then hits the face of the PMT. The oscilloscope takes the two signals, which is shown in Fig. 3.5 and measures the time gap between them. This gap is used to find the time it takes the PMT to take in the light and then output a signal.

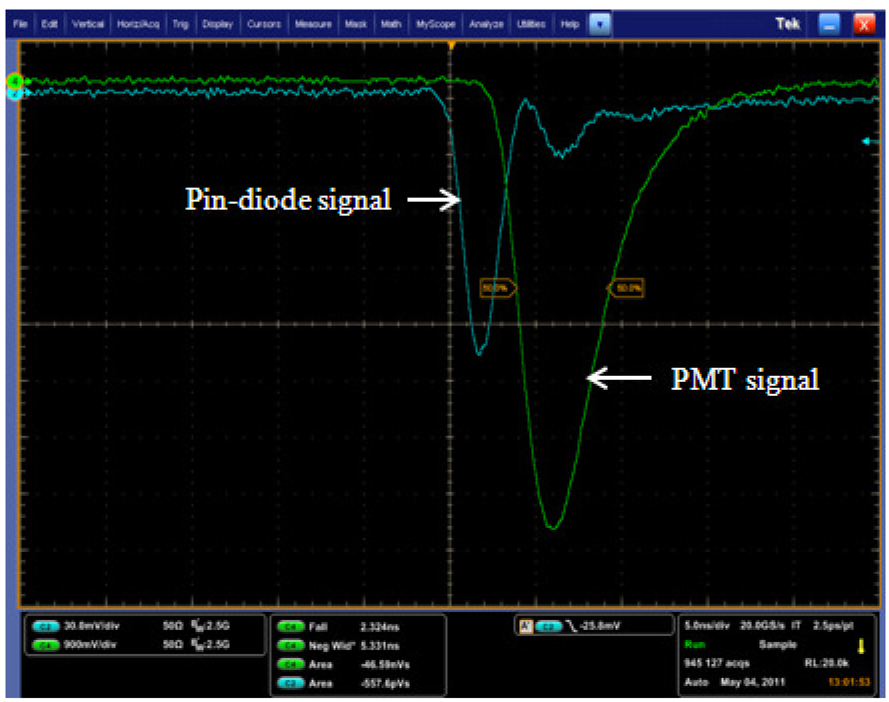

Figure 3.5: The difference between the PMT signal and pin-diode signal on the oscilloscope

The improved visual basic code is used for this test, and all the measurements are saved via the code running in the digital scope.

3.1.4 Single Pulse Linearity

The linearity test is a measure of the PMTs change in gain over varying light intensities. Explicitly, the test measures the output signal of the PMT over a range of light values. The output signals are plotted versus light intensity. A trend line is then fit to the data points to determine the deviation from the linear trend. Basically, the main goal of the linearity test is to measure the correct energy information for each PMT for different light intensities since the light intensity of the Cherenkov light from the fibers fluctuates in real CMS detector at CERN. This light intensity is proportional to the number of electrons emitted from the photocathode surface.

Similar to the timing test, the linearity test uses the same setup that is explained in Section 3.1.3. The schematic representation of the experimental setup can be seen in Fig. 3.4. The only difference is that in the linearity test the neutral density filter wheel is rotated to different positions corresponding to different light reductions. The test measures the current at a constant high voltage but varying light intensities. A measurement is taken and then the light value is decreased and another measurement is taken. This is repeated though a range of decreasing light values. The current values are then plotted versus the light intensities from the PIN diode. A trend line is then fitted and R^2 is then found and used to calculate the percent error from the trend line fitted.

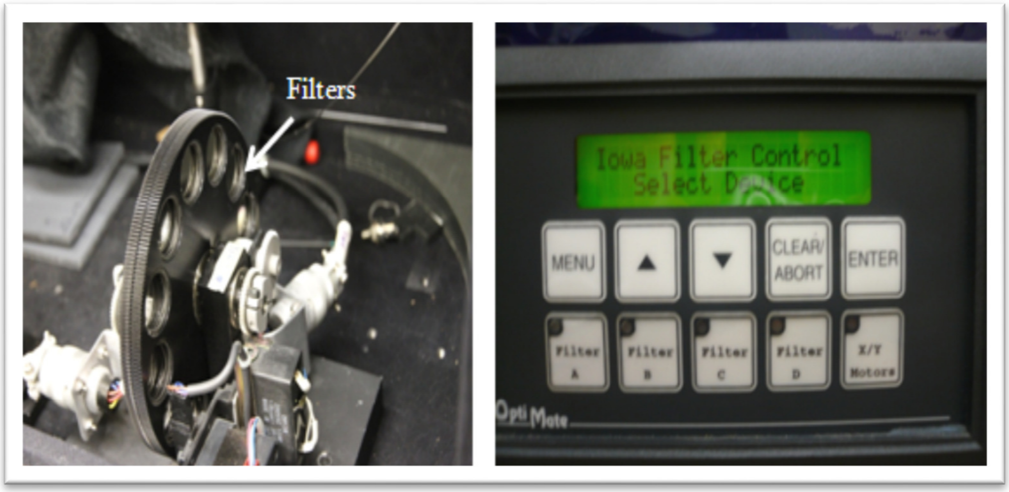

Figure 3.6: The automatic filter control select device and the remote control filter wheel.

In this test we use different density filters in front of the beam that hits of the face of the PMT. Since each filter reduces the light intensity by a different amount, we compare two signals and measure the time gap between them for each filter. For this purpose, we are equipped with an automatic filter control device and a remote control wheel filters. These can be seen in Fig. 3.6.

3.2 Secondary (Batch) PMT Tests

In the second category; cathode surface non-uniformity, double pulse linearity, single photoelectron resolution, anode cross-talks, and after pulse measurements are performed on one randomly selected PMT in each batch (~100 PMTs). In the last category, a lifetime test is performed on only one PMT. In this category, we will concentrate on the four most important test parameters and analyze their data. These are double pulse, surface non-uniformity, after pulse, and lifetime.

3.2.1 Double Pulse

The double pulse test is a measure of the linearity of the photomultiplier tube with two signals with the signal strength ratio 1:1/4. We use different filters to increase the light intensity to reach the "transgression point" where the linear behavior of the double pulse breaks down. The developed experimental setup is shown in Fig. 3.7. As a source blue LED is used and after the light intensity is filtered for the desirable value, the light is carried to the PMT surface by a light guide.

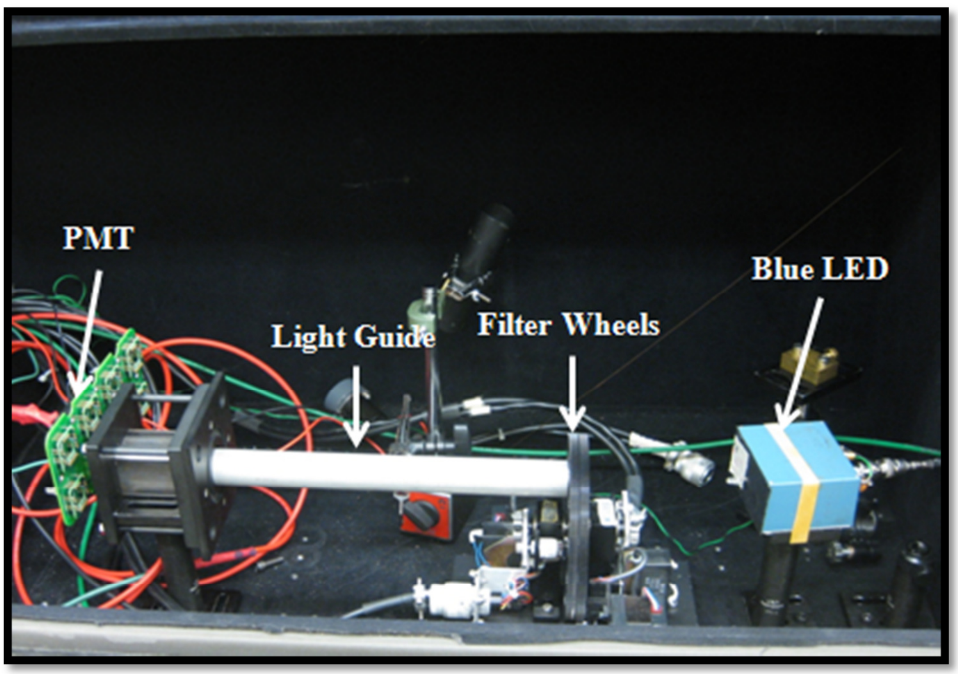

Figure 3.7: The light guide system from the filter wheel to the PMT for D. Pulse test

The two pulse technique is used for the measurements. As Fig. 3.8 shows, two pulses can be seen on the scope and we modify the second pulse for having one-fourth of the amplitude of the first pulse. Then, they are separated by about 25 ns. The peak current values are measured for different light intensities to comprehend the linearity behavior of each PMT.

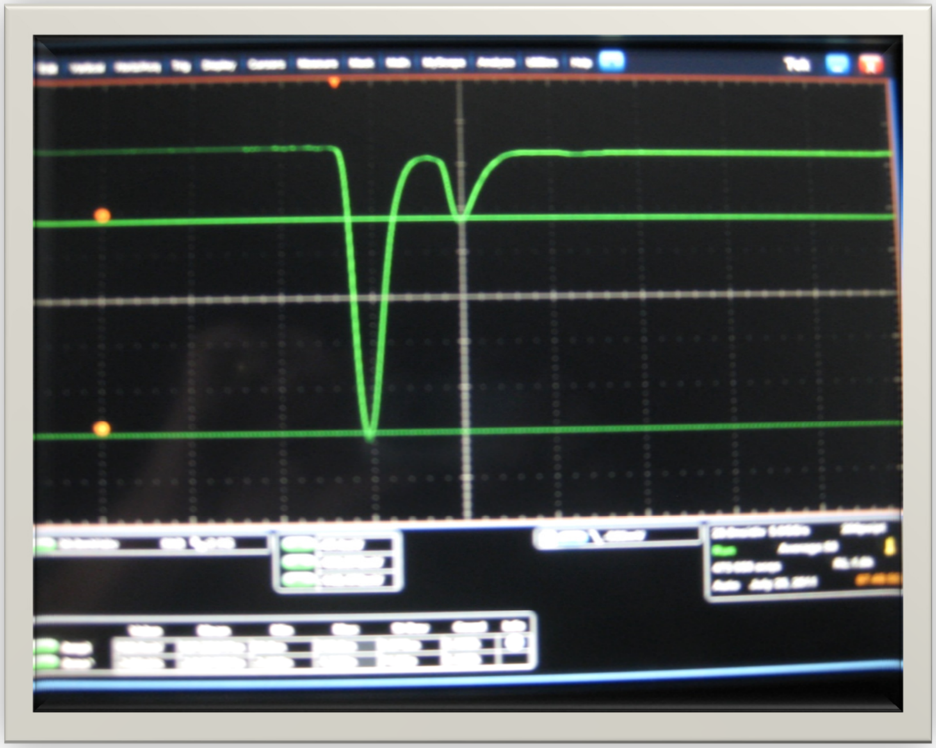

Figure 3.8: The two pulse technique: two pulses with the amplitude ratio 1:1/4

3.2.2 Surface Non-Uniformity

The surface non-uniformity is a measure of the ‘hot spots’; i.e., sensitivity and uniformity of the active area of the PMT. The R7600U-100-M4 types of PMTs from Hamamatsu have four anodes. We scan the active area (18mm×18mm) of each PMT face in steps of 1mm×1mm, which is shown in Fig. 3.9. For this test, the computer controlled

X-Y scanner is used and the fiber starts at the right bottom of the PMT surface and scans the entire surface step by step.

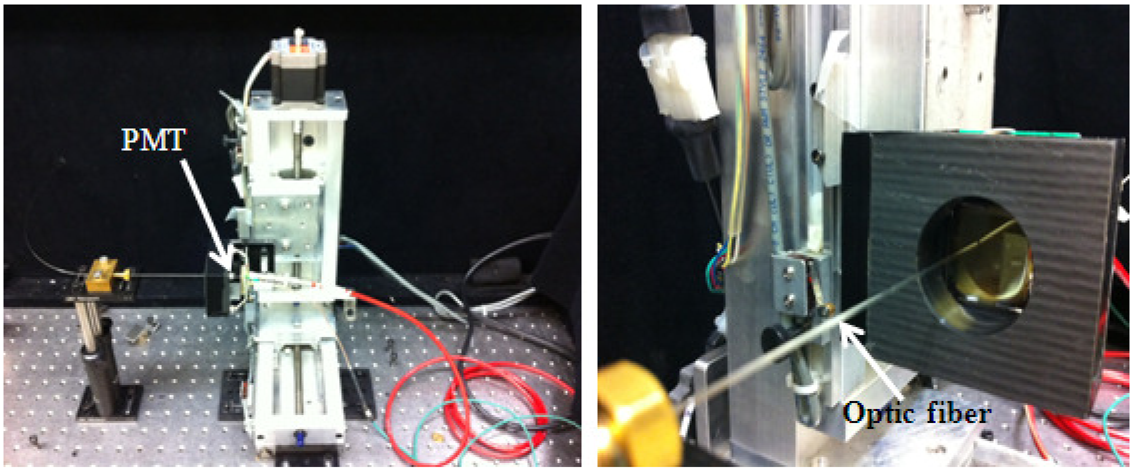

Figure 3.9: The computer controlled X-Y scanner and the fiber controlling each cell of the PMT.

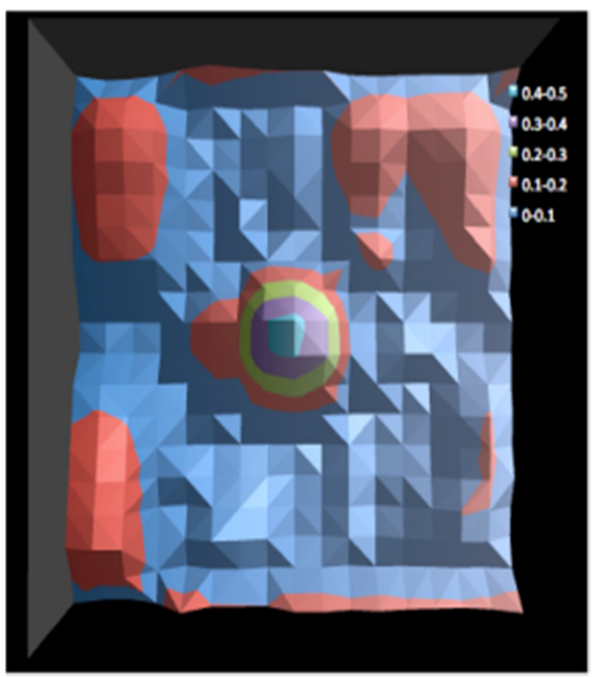

Figure 3.10: The 3-D plot of the non-uniformity deviation of the PMT (S.N: JA0883)

This test for each PMT approximately takes 10 hours and collects data of 10,000 signals from each step. At the end, we have the output data for the active 18mm×18mm area categorized in 18 cells with the area of 1mm×1mm. The calculations of the average deviations of the cells are made and plotted as shown in Fig. 3.10. The average deviation of the surface non-uniformity should be less than 30%; this is a requirement of the HF. If the result is in this range, the PMT is a good candidate for collecting the data of forward jets.

3.2.3 After Pulse

There might be some residual gases inside the PMT although the interior of a PMT is a vacuum chamber. Photoelectrons (secondary emission electrons) can ionize the atoms of the residual gases. If these positive ions strike to the photocathode or some stages of the dynodes, unexpected secondary shower of electrons may be emitted. They can cause a large unwanted output signal. The unwanted signal is called an after pulse. Generally, the time difference between the real event signal and the unwanted output signal is about 500 ns. This time difference is divided by 5 and in each 100 ns we observe the after pulse signals of the PMT by using a data acquisition system. The after pulse measurement is aimed to measure these unwanted signals and attempt to separate them from the real signal.

The setup for after pulse measurement is basically same as the X-Y surface scan test. The surface scan device (Fig. 3.9) is used as a stand for the PMT and the light guide. The metal light guide is fixed into X-Y scanning device and the PMT holster is attached to the end of the light guide, where the PMT exactly faces the light guide. The pulsed light from the LED is sent via scintillating fiber through to the light guide onto the face of the PMT to provide a signal. The data acquisition system records this signal and also any pulses that occur after 500 ns. If there is any signal observed, we try to figure out the reason and get rid of it.

3.2.4 Lifetime

Since the operation of the CMS experiment will extend for many years, each constituent of the experiment should preserve its efficiency as long as the experiment continues. PMTs as one of the key parts in this test should be long running without reducing their qualities. However, each PMT has a lifetime limit that must satisfy the CMS-HF specifications in Table. 2.1.

The lifetime test is a measure of the anode gain changes as the PMT's anode accumulates by an amount of charge (C). Only two PMTs are tested and burned for this purpose. The PMTs are placed in a light tight box for two independent tests with a tungsten bulb as a light source. A neutral density filter and a blue light filter are used to reduce the light intensity. The PMTs are supplied with 1100 volts, which is higher than the optimum expected value of CMS. The gains of the each PMT is measured and recorded before and after the test.

During the operation time of the CMS, under the collisions, (approximate anticipated 10 years) PMTs might accumulate 1500 C (Coulombs). To be ready far beyond this value, each PMT is tested to twice the value expected at CMS, and the gain change is measured. In the previous tests, it was seen that the gain of two PMTs dropped to half value or less, while they are accumulated with 3000 C. It can be seen in Figure 3.11.[5]

Each month 50 C is accumulated to the each PMT so this test takes approximately 6 months to reach 3000 C.

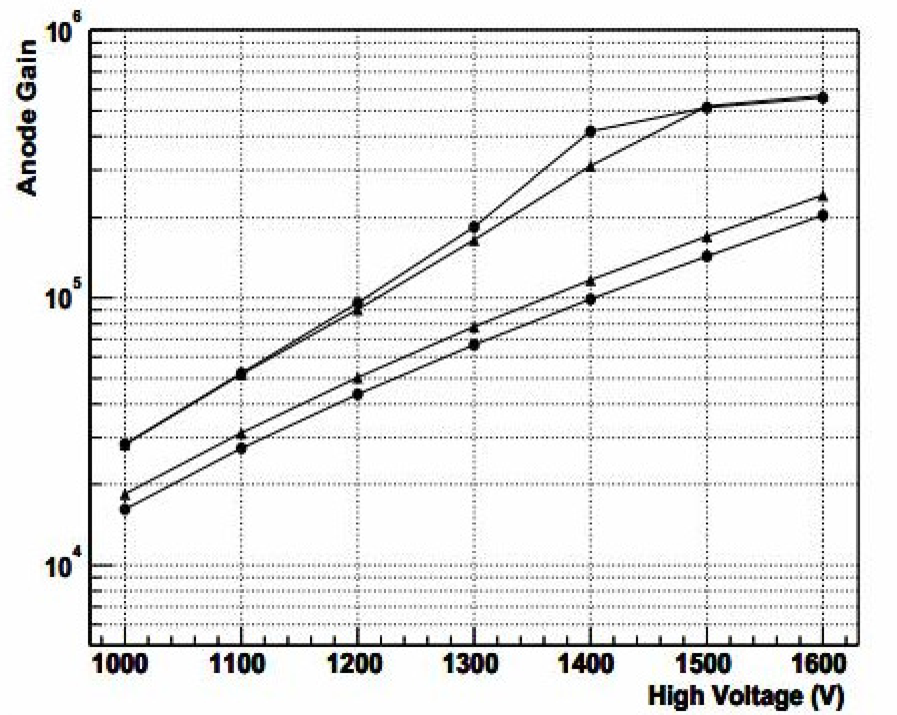

Figure 3.11: The measurement of the gain verses voltage applied before and after the lifetime test [10].

[5] This figure is from the previous test results conducted at the University of Iowa and it is taken from Dr. Akgun's Ph.D. dissertation.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Primary Test Results

In this category, all the data from 900 PMTs is gathered for dark current, gain, timing and linearity. We check photomultiplier tubes one by one to be certain whether or not they satisfy the specifications. Overall, the data was plotted for 900 PMTs to clearly see how PMTs would behave under the real conditions explained in Chapter 2 at the experiment after they implanted to the HF calorimeter.

4.1.1 Dark Current

The dark current distribution in Fig. 4.1 shows that the dark current of most of the tubes is below 0.5 nA when the high voltage is at 600 V. When the high voltage is increased to 900 V, the dark current value of the most PMTs approaches 1 nA (see in Fig. 4.7). This is a good result because this value is much lower than CMS-HF's required value, which is 1 nA for each anode at 800 V and 4 nA for four anode PMTs (see in Table 2.1). Overall all the PMTs dark current values are much less than the required value. This means that these PMTs absolutely show good response and can be used in the real experiment at CERN. Ideally, their noise would be much lower than the signal.

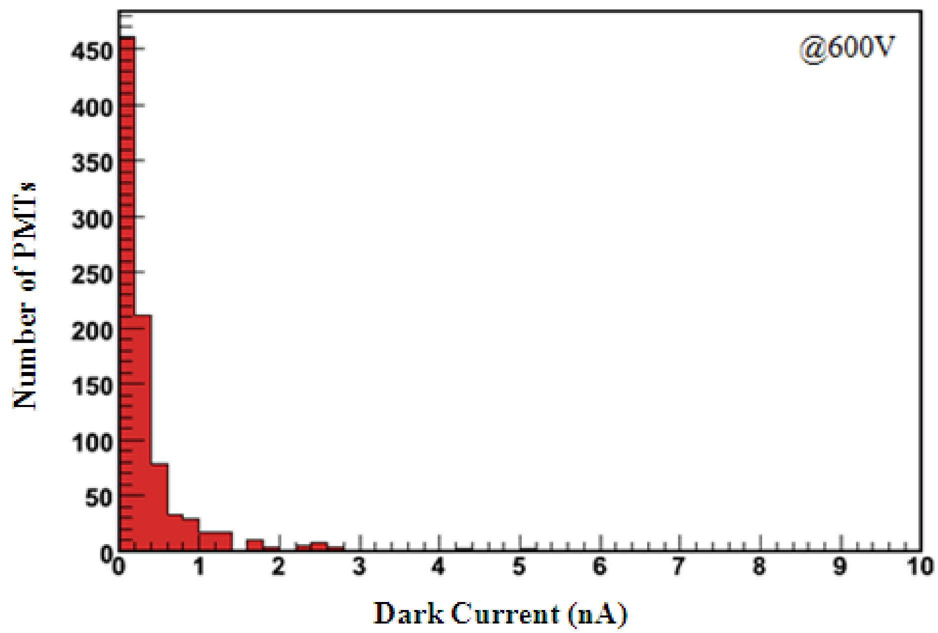

Figure 4.1: Dark current distribution of 900 PMTs at 600 V.

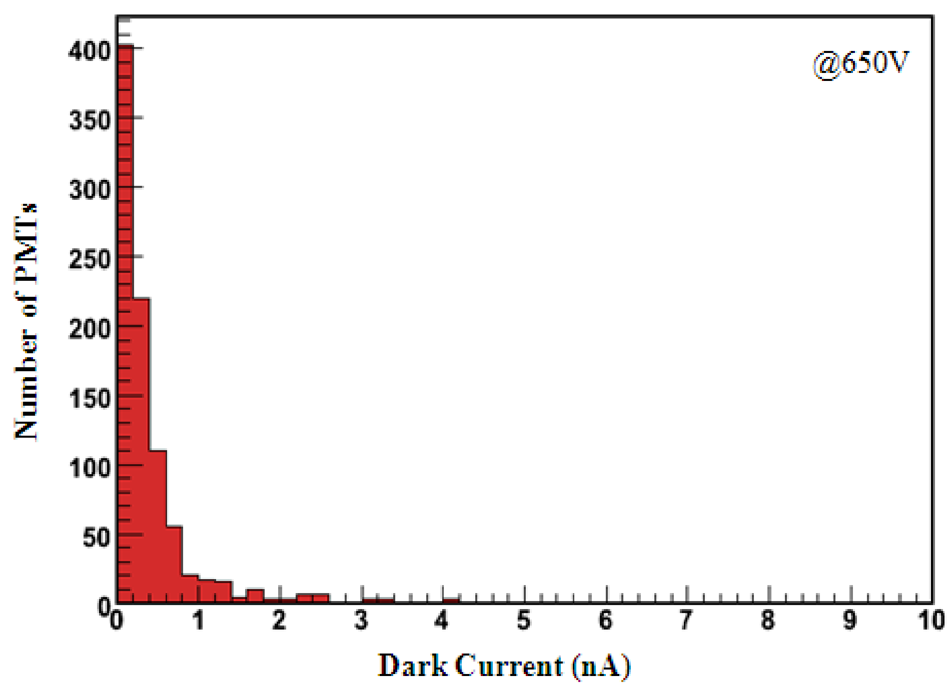

Figure 4.2: Dark current distribution of 900 PMTs at 650 V.

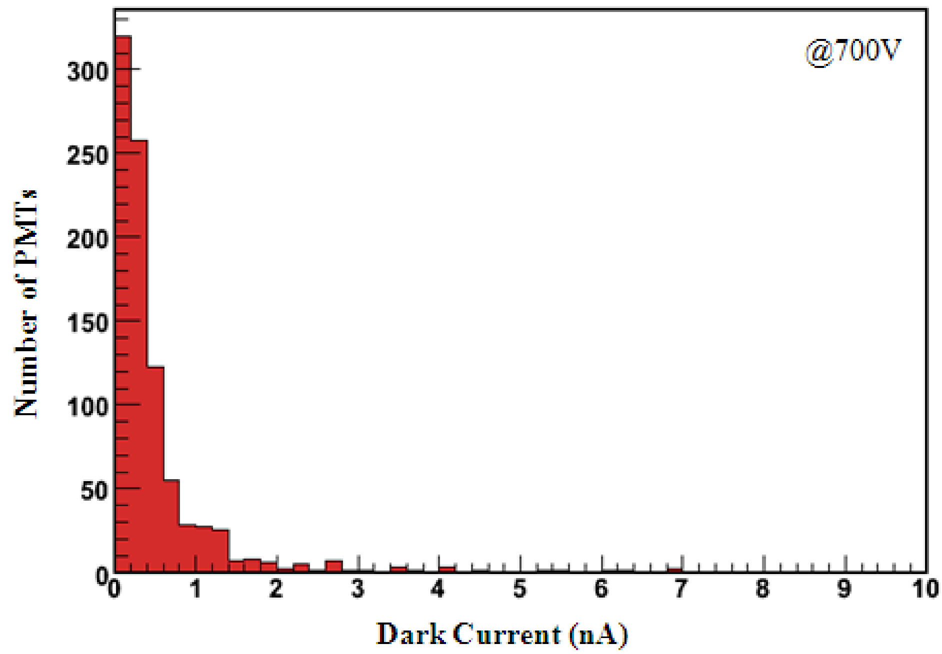

Figure 4.3: Dark current distribution of 900 PMTs at 700 V.

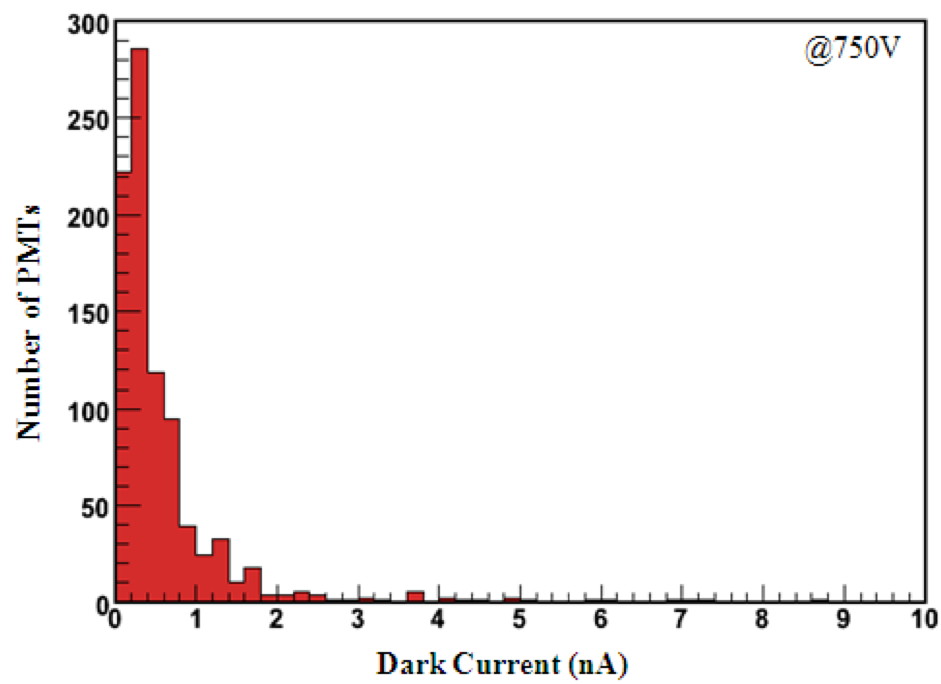

Figure 4.4: Dark current distribution of 900 PMTs at 750 V.

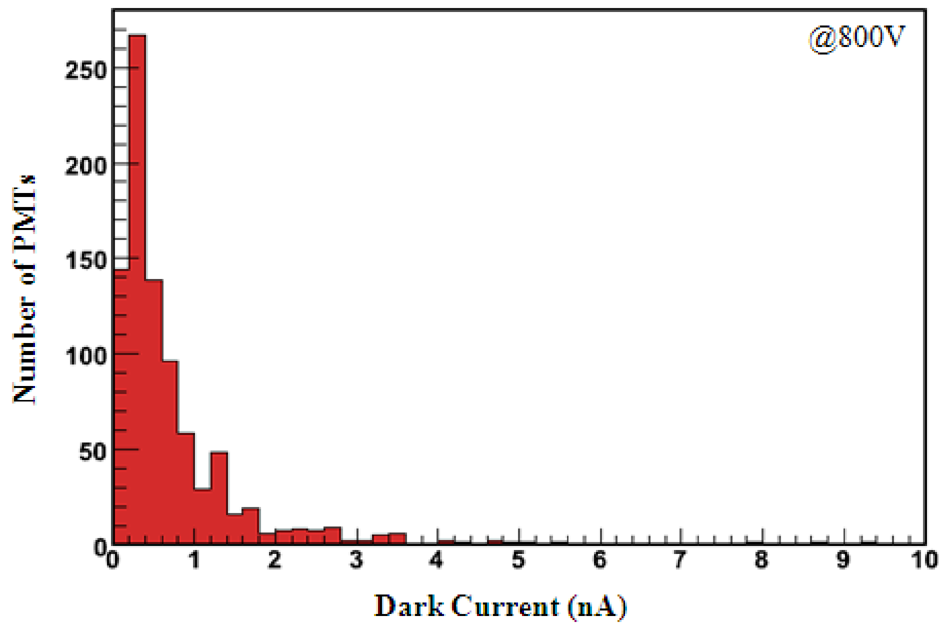

Figure 4.5: Dark current distribution of 900 PMTs at 800 V.

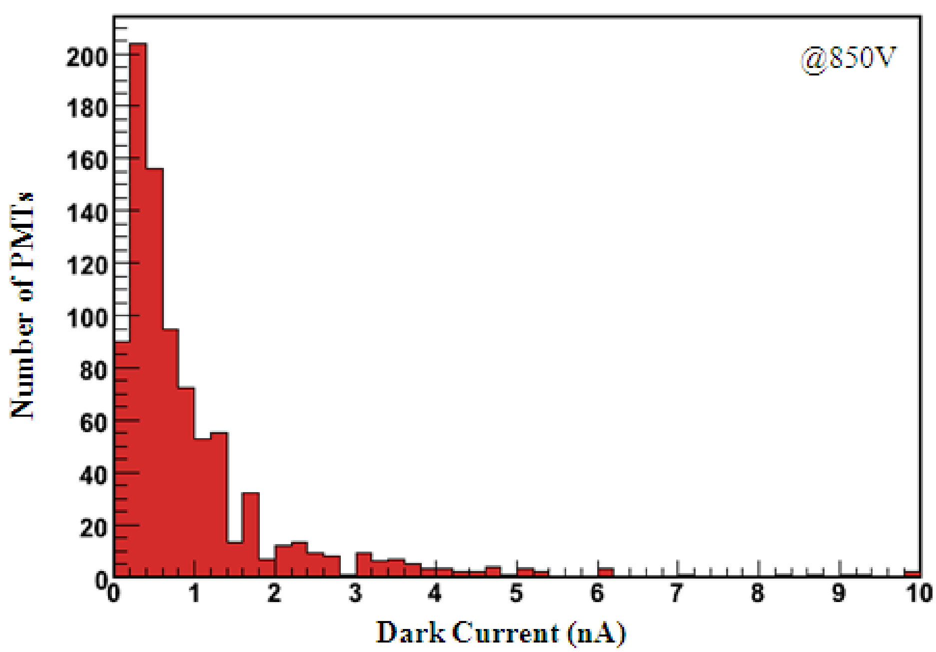

Figure 4.6: Dark current distribution of 900 PMTs at 850 V.

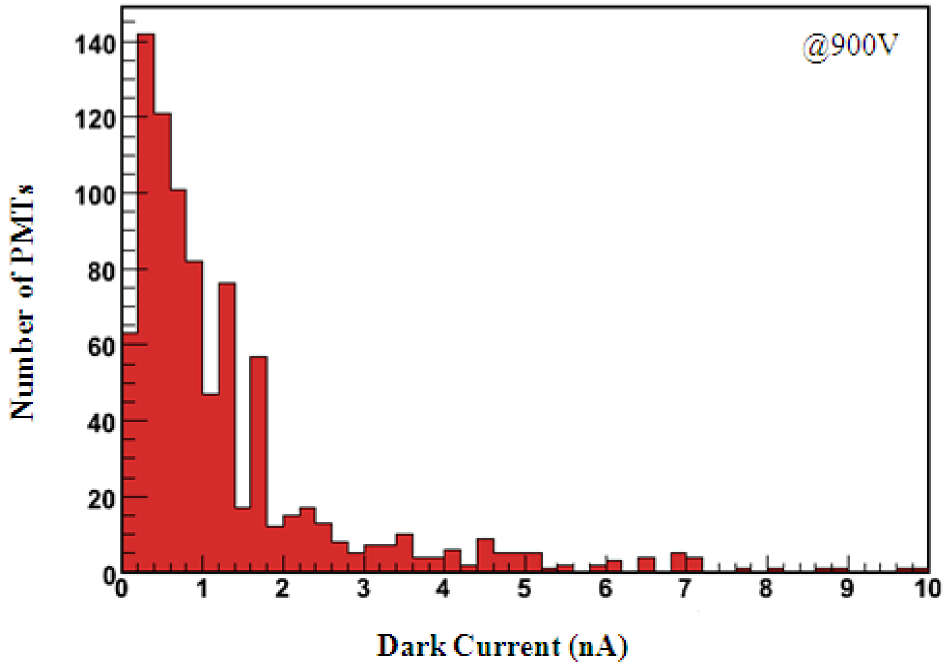

Figure 4.7: Dark current distribution of 900 PMTs at 900 V.

4.1.2. Gain (Anode and Cathode)

Gain values are expected to be almost the same for the each PMT because they have the same cathode material, size and four anodes. CMS-HF requires that each PMT needs to have a gain higher than 1×10^6 at 800 V. This is the lower limit of the readout electronics and the expected value of the Cherenkov light intensity. Because the tube's gain changes with voltage applied, the high voltage at the required value needs to be taken account.

Between 600 V and 700 V the gain appears lower than the specified value but this is acceptable until the voltage at 800V (see Fig. 4.8, 4.9 and 4.10). As can be seen in Fig. 4.10, the gain distribution is around 2×10^6 and this is twice as much. Gain measurements over the 900 PMTs at 900V can be seen in Fig. 4.14.

For 900 V the gain distribution is somewhat wide. This is because of the larger statistical uncertainty. However, the result over 900 PMTs perfectly fits the gain specifications of CERN. As can be seen in the graph the gain is greater than 10^6. Generally, most of the PMTs have gain value higher than the required value when the high voltage is 800 V or higher.

Hamamatsu R7525HA type photomultipliers were used in the previous tests for the earlier HF upgrade studies [1] and the median gain was found over 200 PMTs is about 5×10^4. It is much lower than the value we reached and this proves the 4 anode R7600U-100-M4 type PMTs advantages over the other PMTs.

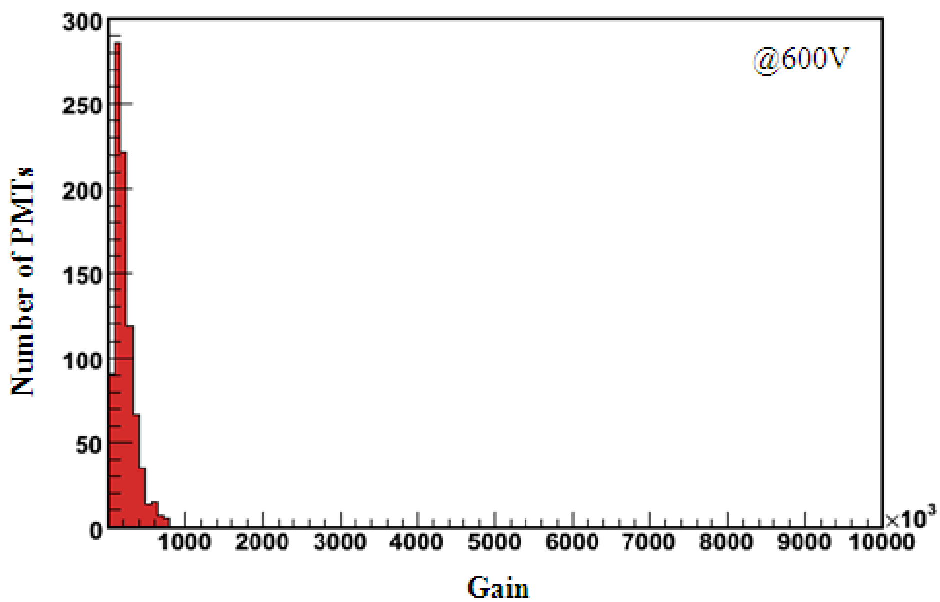

Figure 4.8: Gain distribution of 900 PMTs at 600 V.

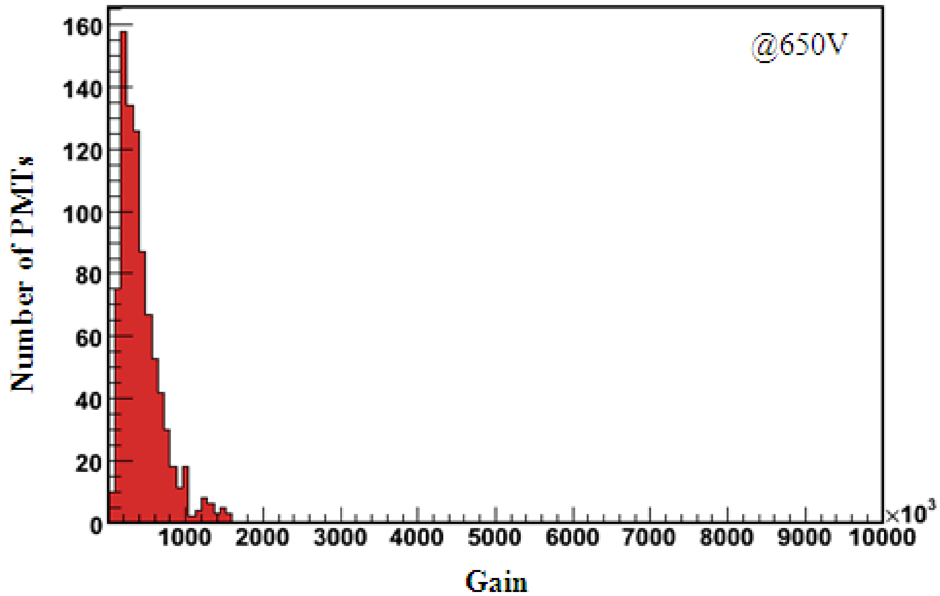

Figure 4.9: Gain Distribution of 900 PMTs at 650 V.

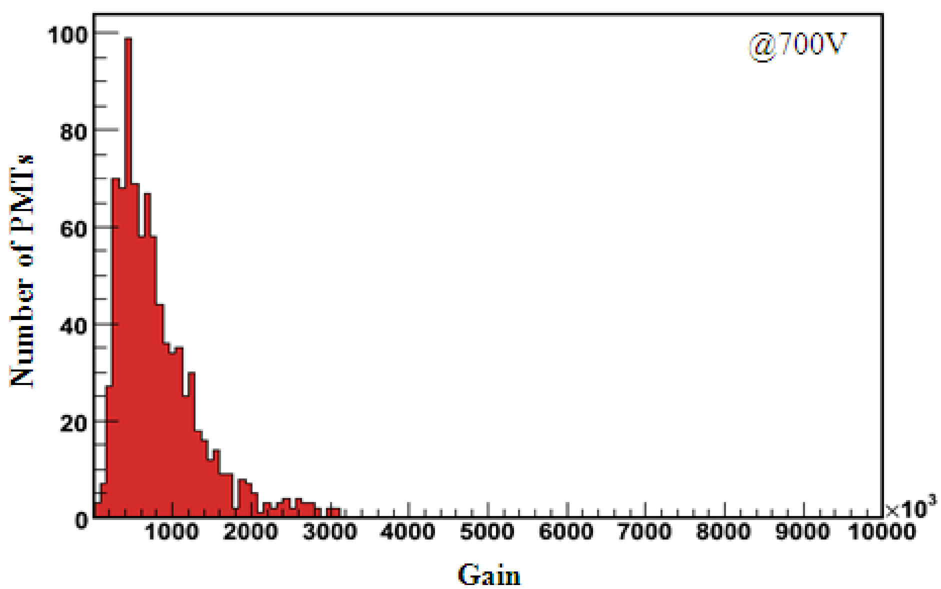

Figure 4.10: Gain Distribution of 900 PMTs at 700 V.

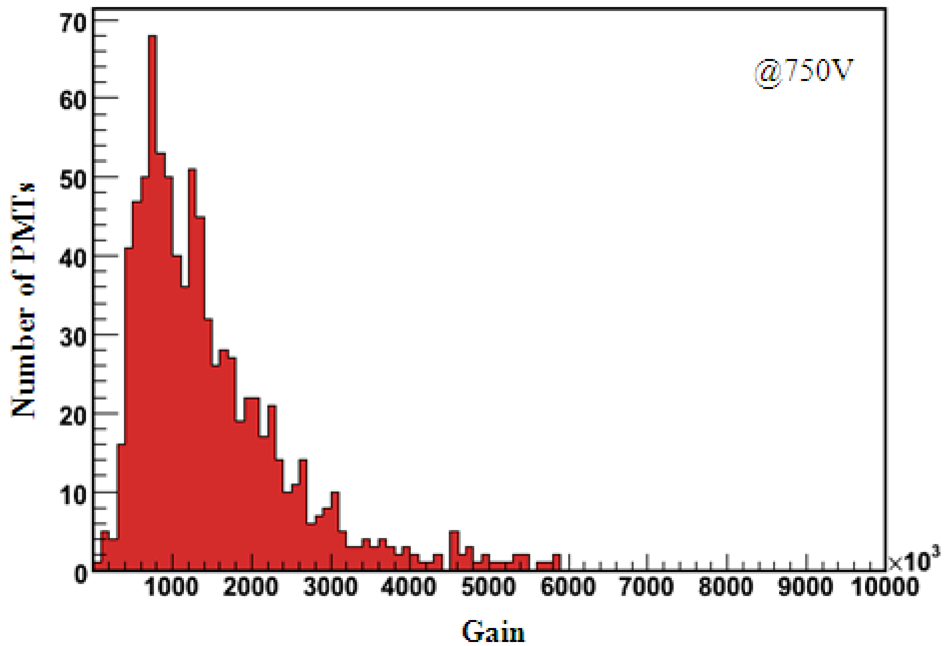

Figure 4.11: Gain Distribution of 900 PMTs at 750 V.

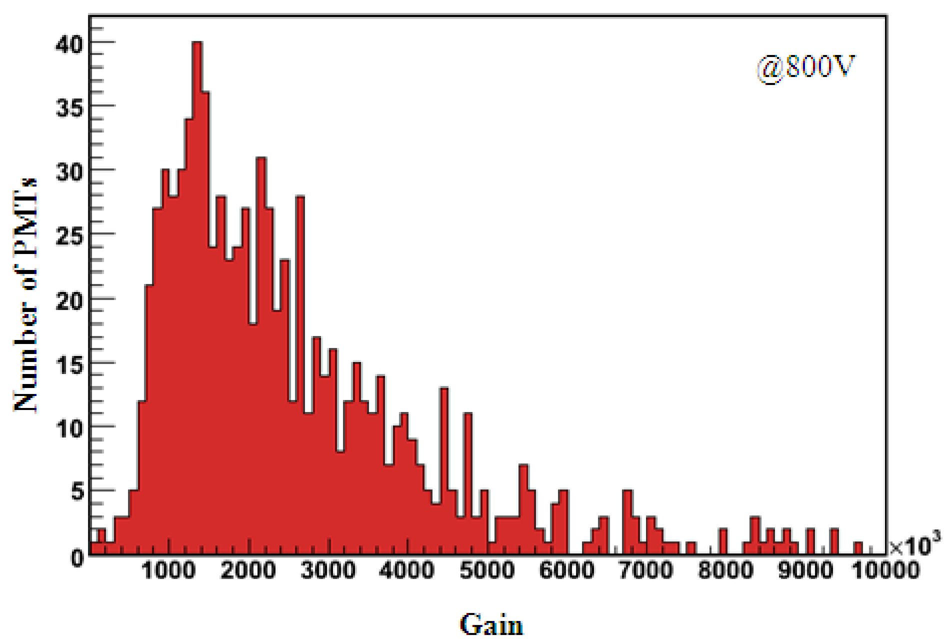

Figure 4.12: Gain Distribution of 900 PMTs at 800 V.

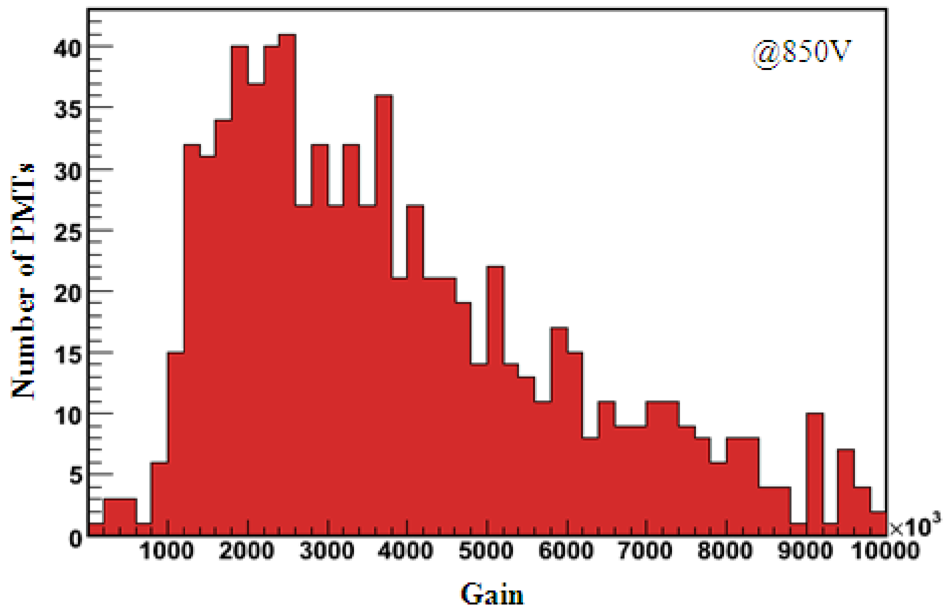

Figure 4.13: Gain Distribution of 900 PMTs at 850 V.

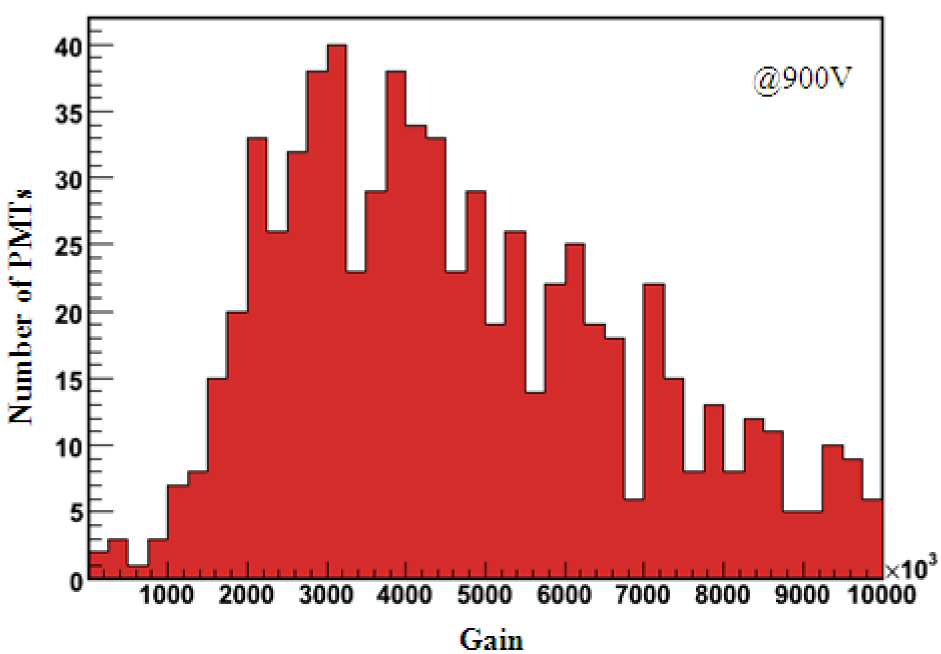

Figure 4.14: Gain Distribution of 900 PMTs at 900 V.

4.1.3 Timing

Fig. 4.15, 4.16, 4.17 and 4.18 respectively show the distribution of rise time, pulse width, transit time and transit time spread. The specified value for the rise time is any value smaller than 2 ns but in our measurements we have found that the rise time is around 2.2 ns. Although the rise time result is higher than the specified value, the limit of 2 ns is not that much lower than our measurement, and it is within a reasonable distance.

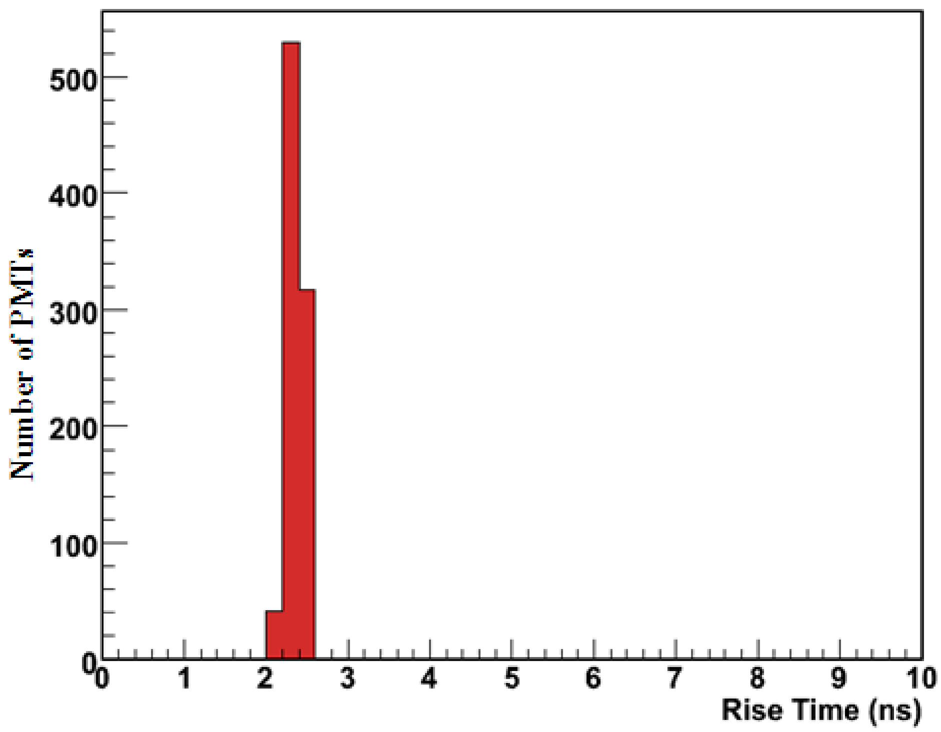

Figure 4.15: Rise time distribution for 900 PMTs.

Pulse width measurements in Fig. 4.16 show that all the results are in the 5-6 ns range. This is significantly smaller than the limit set by CMS-HF; the requirement is a pulse width smaller than 15 ns.

As can be seen in Fig. 4.17, the transit time distribution is narrow between 5-6 ns. Also, all of the tubes have almost the same transit time value. As shown in Tab. 2.1, transit time is expected to be maximum 25 ns so 5-6 ns range is impeccable. This is a perfect result for smooth and stable operation of the calorimeter.

The last timing quantity is transit time spread which is in the 0.2-0.3 range in the Fig. 4.18. Because the transit time spread gives the deviation of the 100 transit time value, 0.2-0.3 range is an exceptional result for the experiment.

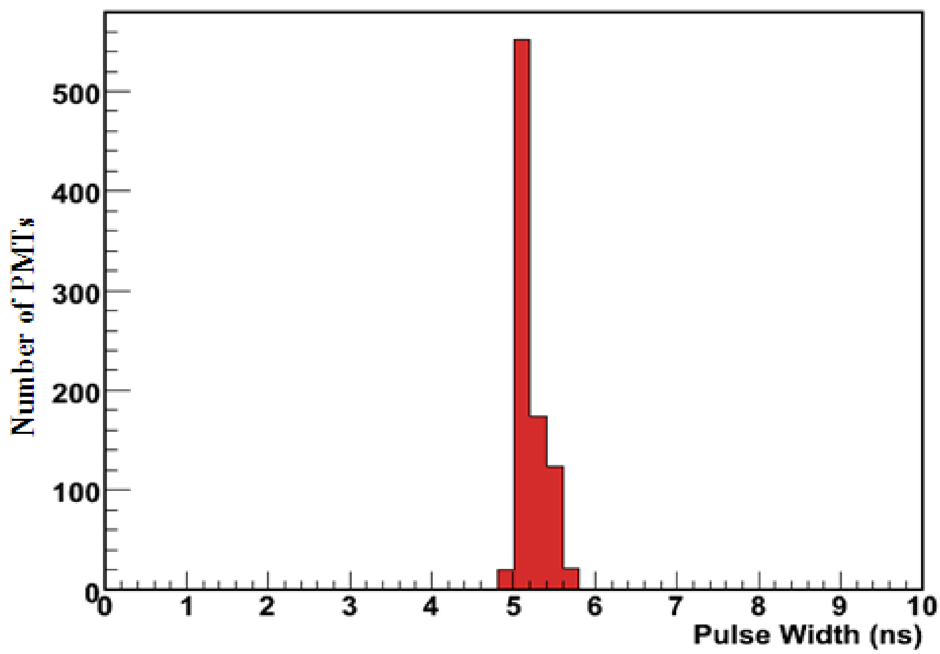

Figure 4.16: Pulse width distribution for 900 PMTs.

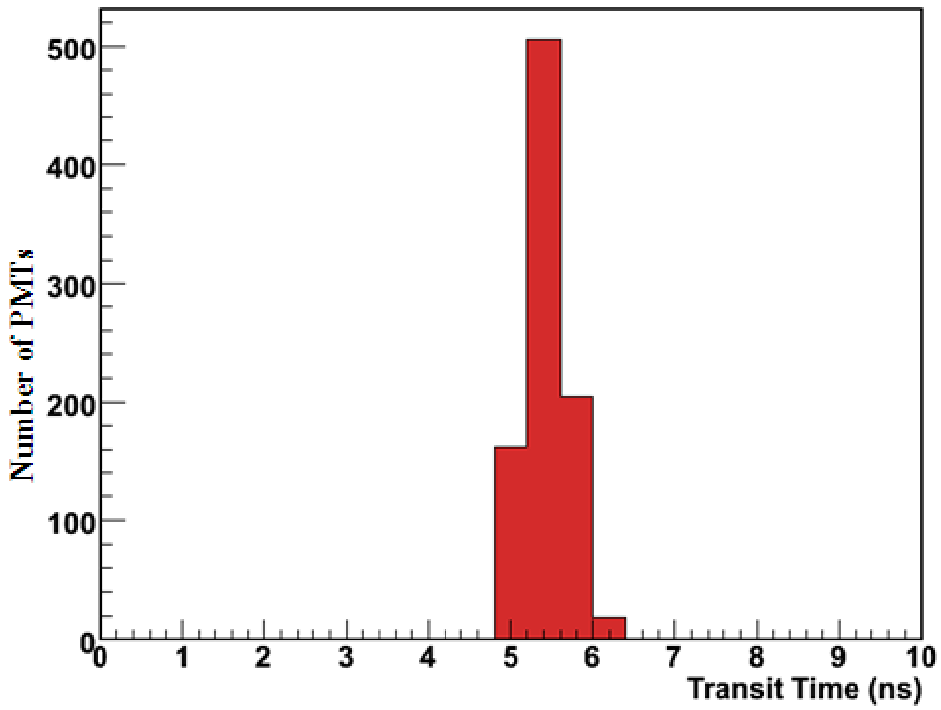

Figure 4.17: Transit time distribution for 900 PMTs.

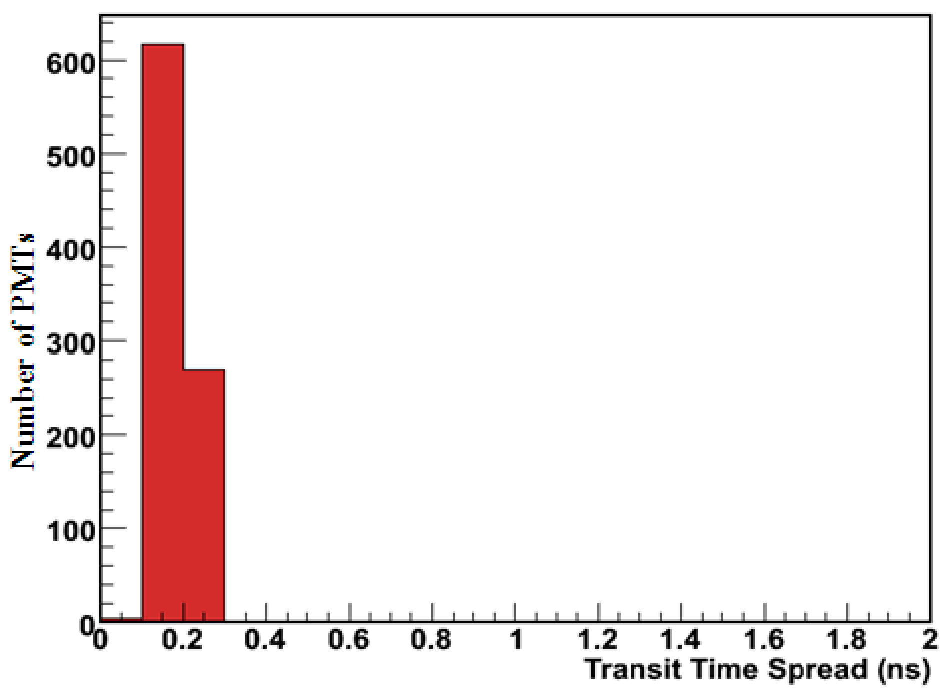

Figure 4.18: Transit time spread distribution for 900 PMTs.

4.1.4 Single Pulse Linearity

Linearity results show good agreement with the expectations. Almost all of their values fell less than 1% which is a very good result, see in Fig. 4.19. This shows that the PMTs respond in a very linear manner with the increasing light intensity. If the output of the signal (current) is proportional to the light intensity and if the proportionality constant stays the same with changing intensity, the PMT is called as a linear tube. This allows the PMTs to be effective in multiple light intensity scenarios. These PMTs are adequately linear for being a good candidate for the HF calorimeter in the CMS detector at CERN.

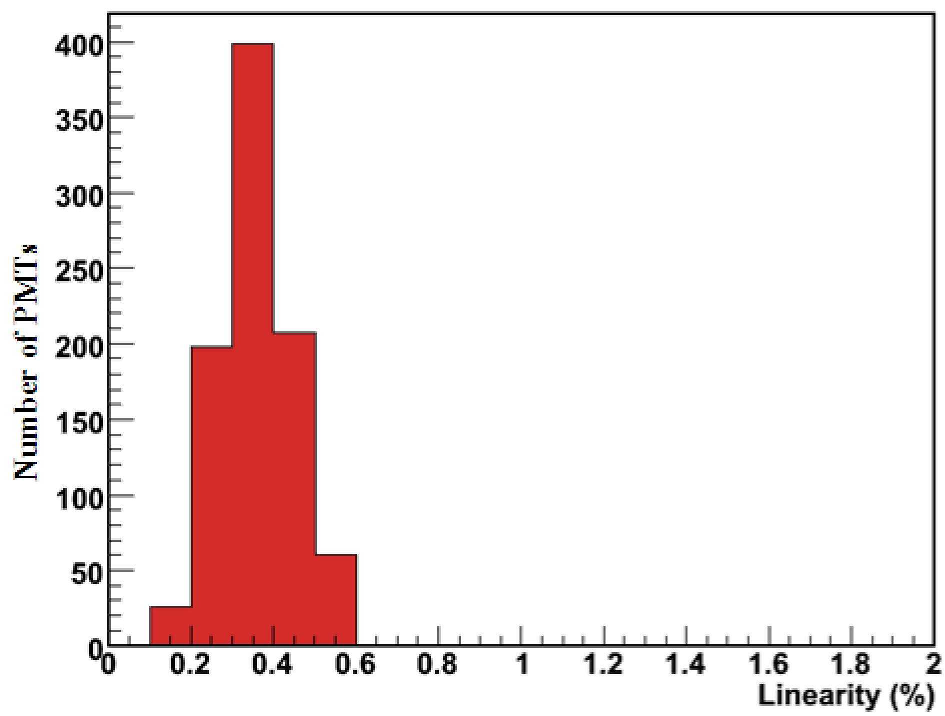

Figure 4.19: Single pulse linearity distribution for 900 PMTs and x-axis shows the percentage deviation.

4.2 Secondary Test Results

Double pulse, surface-non uniformity, after pulse and life time experimental setups are currently developed and they are described in Sect. 3.2. Also, some expected results from the previous studies are discussed in Sect. 3.2. Once the measurements are completed and the results are ready, the plots will be drawn and outcomes will be discussed.

Lifetime measurements are currently performed on two phototubes up to 50 C, and there is not any significant change observed. Each PMT will be tested to 3000 C and the gain change distribution will be observed.

CHAPTER 5

SUMMARY AND CONCLUSION

There is a rejection limit defined based on the specifications of the calorimeter (see in Table 2.1). Among the 900 photomultiplier tubes evaluated for the HF calorimeter only 30 of them were rejected. Of the 30 PMTs rejected, 19 of them were rejected for high dark currents. The other 11 PMTs failed due to gain values that were too low. Overall, they have the same timing characteristics and they satisfy all of the CMS-HF requirements. Hence, they might be ideal candidates in the real experiment at CERN and they would help to reveal the missing piece in the particle physics puzzle by detecting high energy jets and improving the measurement of the missing transverse energy.

We will test 900 more PMTs and compare their results with the test of the first 900. After all 1800 have been tested we will send the PMTs to CERN for installation for the upgrade. After we install them in the readout boxes they will be used for data collection and reconstruction of collision events in the HF Calorimeter.

The tests started in January 2011 and still continue. The anticipated date is June, 2012 to finish all the measurements. After the PMTs are separated in terms of their quality, they will be shipped to CERN.

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