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Comparison of PMTs from three different manufacturers for the CMS-HF Forward Calorimeter

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Abstract

The builders of the CMS forward hadron calorimeter established a set of specifications for readout PMTs that reflected the physics goals and mechanical needs of the CMS experiment. Three manufacturers, Hamamatsu, Photonis (Philips), and Electron Tubes (EMI), provided candidate PMTs based on these initial requirements. Timing, gain, and dark current properties and single photoelectron spectra of these candidate PMTs were measured. Results show that Hamamatsu PMTs (R7525HA) conform best to the specifications of the HF Forward Calorimeter.

1 Introduction

The HF Calorimeter samples particle showers in an iron absorber by detecting the Cherenkov light. The Cherenkov light produced in the fibers will be detected and measured with phototubes. The quality and reliability of these PMTs are essential to the operation of the calorimeter.

Three PMT manufacturers, Hamamatsu, Photonis (Philips), and Electron Tubes (EMI), provided us with candidate tubes that met the minimum requirements for the HF calorimeter. These candidate tubes were tested for timing, gain, dark current, and single photoelectron resolution.

Overall evaluation of the candidate PMTs was based on the results of all these tests. Hamamatsu R7525HA PMTs were chosen as the optimum choice for the HF Forward Calorimeter. The evaluation procedure for the PMTs is explained below.

2 HF Calorimeter

The HF calorimeter is designed to be sensitive to the pseudorapidity region ($3 < \eta < 5$) for processes important in searching for heavy Higgs and SUSY particles which produce forward jets. Information coming from the HF will also help improve the determination of missing transverse energy.

There are two HF Forward Calorimeter units, one at each end of CMS. Each unit has an active radius of 1.4m and consists of iron absorbers, fibers embedded into the absorbers, and phototubes. The embedded fibers will have two different lengths to differentiate between shower processes. Longer fibers (1.65 m) will provide light from EM and hadronic showers in the absorber. Shorter fibers (1.43 m) will only see the hadronic showers[1]. The long and the short fibers are read out by separate PMTs. The iron absorber length (1.65 m) is 10 nuclear interaction lengths.

The fast charged particles in the shower produce Cherenkov light in the quartz fibers. These particles are mostly relativistic electrons and positrons with speeds above the Cherenkov threshold for quartz. The HF calorimeter is insensitive to the low energy charged particles and neutrons that are abundant in hadronic showers. (Also it will not be affected by induced radioactivity.)

Being sensitive to the hard particle core of the shower has other benefits. The distribution of the relativistic particles in the shower shows a narrow profile, even narrower than its corresponding Molière radius. It is also shorter than the full shower profile. Hence using Cherenkov-radiation-in-quartz-fiber method enables us to have a more compact design for the HF Forward Calorimeter. This type of shower detection is fast since the tail in the time distribution is caused by slower particles that do not produce Cherenkov radiation. These features of the calorimeter have been confirmed in our prototype tests at CERN[1].

Each HF module is divided into 18 wedges. Every wedge consists of about 2400 stacked parallel iron plates each with 5mm thickness. Grooves are machined lengthwise along each plate and quartz fibers are inserted in these grooves. These groves are separated from each other by 5mm both vertically and horizontally. Short and long fibers are placed in each tower in alternate grooves. All the long fibers from a tower will be put together in a bundle and attached to a phototube. Similarly, all the short fibers from a tower will be attached to another phototube. There will be 48 PMTs per wedge. Reliable operation of the HF Forward Calorimeter depends mostly on the phototubes.

3 HF Requirements for PMTs

Specifications of the PMTs to be used in the HF calorimeter are listed in Table 1. These specifications are meant to address the various issues in the construction and operation of the HF calorimeter. Operating conditions in the LHC, the mechanical construction of the HF calorimeter, and the way the fibers generate Cherenkov light and transport this light to the PMTs determine some of the physical parameters of the PMTs needed in the HF. Location and the available volume for the PMTs in the HF calorimeter define the size of the PMTs. The amount of radiation expected at the HF location and the environmental conditions, such as temperature and humidity, put limitations on the size, packaging, and materials used in manufacturing the tubes. The intensity and the wavelength of the Cherenkov light generated in the fibers will guide us in selecting the window material and the minimum quantum efficiency. These initial requirements are listed in the top part of Table 1. The second half of the table lists those parameters that are related to the operation of the HF specifically.

Table 1: **Summary of the HF-PMT Specifications.**

Basic requirements	
Window Material	Borosilicate glass
Effective Photocathode Diameter	22 - 28 mm, head-on
Quantum Efficiency	$>$ 15 percent (400-500 nm)
Photocathode Lifetime	$>$ 200 mC
Stability	$< \pm$ 3 percent within any 48 hr. period
Envelope	opaque and HV conductive coating
Operational requirements	
Anode Current vs Position	$<$ 20 percent variation with 3 mm spot scan
Gain	10^4 to 10^5, 10^5 at less than 0.75 x V_{KA}(max)
Single Photoelectron Resolution (rms/mean of SPE peak)	50 percent or better[a]
Pulse Linearity	$\pm$2 percent for 1-3000 photoelectrons
Anode pulse rise-time	$<$ 5 ns
Transit Time	$<$ 25 ns preferred
Transit Time Spread	$<$ 2 ns preferred
Pulse width	$<$ 15 ns FWHM
Gain (1/2)-lifetime	$>$ 1500 C
Average Cathode Current	$<$ 1 nA (g = 10^4)
Average Anode Current	$<$ 10 μA (g = 10^4)
Anode Dark Current	$<$ 2 nA (g = 10^4)

[a] In this paper, all the resolution measurements are given in terms of FWHM/peak position which yields values about 2 to 2.5 times larger than rms/mean method (FWHM = 2.534σ for a gaussian).

4 Evaluation Procedure

Manufacturers were asked to propose specific PMTs meeting the requirements summarized in Table 1. The suggested PMTs were tested under varying conditions to determine the dynamic range of the operating parameters. A PMT that was low-cost and conformed well to the requirements over a wide range of conditions was selected.

Three manufacturers, Hamamatsu, Photonis, and Electron Tubes, responded and provided us with candidate tubes. These are listed in Table 2.

These tubes were tested for the operational requirements [2, 3], specifically; the timing characteristics (anode pulse width, rise-time, transit-time, and transit-time spread), gain, dark current, single photoelectron resolution spectrum, and spatial uniformity of the photocathode surface [4].

Most of the parameters were measured at a nominal tube gain of 10^4, since the HF PMT readout system was designed to accept low amplitude signals. With the expected Cherenkov light intensity and the required photocathode quantum efficiency, this gain will be sufficient to generate an output pulse compatible with the readout system requirements.

Since there were more than one sample tube for some of the PMT types, all ten of the PMTs were not always tested. A representative sample of measurements for each PMT type was considered sufficient. All the tests were performed on all the PMT types even if a specific PMT did not perform in accordance with the HF requirements in a previous test.

4.1 Timing Measurements

The time response of the PMTs, including pulse width, rise time, transit time and its spread, are determined together in the same setup.

The transit time is the travel time of the photoelectrons from the photocathode to the anode via the dynodes. This transit time depends on the voltage applied to the tube. It also depends indirectly on the electrode structure, since

Table 2: **Candidate PMTs and the manufacturers.**

Manufacturer	Type	Serial Number	Base used
Hamamatsu	R7525HA	ZC9898	Resistive[a]
Hamamatsu	R7525HA	ZC9900	Resistive[a]
Hamamatsu	R7525HA	ZC9903	Resistive[a]
Hamamatsu	R7525HA	ZC9957	Resistive[a]
Photonis	XP3182/D1	99023	Resistive[b]
Photonis	XP3182/D1	99021	Resistive[b]
Photonis	XP2960	12031	Resistive[c]
Photonis	XP2960	12033	Resistive[c]
Electron Tubes	D843WSB	102	Cockroft-Walton[d]
Electron Tubes	D844WSB	103	Cockroft-Walton[e]

[a] Hamamatsu E2624MOD resistive base
[b] Homemade resistive base with a voltage divider ratio of 3-1-1.5-1-1.1-2.1-2.5-4.4-3.3 for maximum linearity.
[c] Photonis VD189 resistive base
[d] Electron Tubes PS1806 Cockroft-Walton base
[e] Electron Tubes PS1807 Cockroft-Walton base

the electrode structure determines the electric field applied to the electrons.

Transit time variations between different events are caused by different impact points on the photocathode. Fast tubes are designed to minimize these variations [5, 6]. However, there is still some fluctuation in the transit time. These fluctuations produce a transit time spread (TTS).

Other timing characteristics, such as pulse width and rise time, are also important quantities. Pulse width is the FWHM of a pulse. Rise time is defined as the time for the signal to go from 10% to 90% of its maximum amplitude. Total time for the detection process would be the sum of the transit time and the pulse width.

In our timing measurements (see Fig. 1), a 337 nm nitrogen laser (LSI VSL-337 ND) was used as the light source. The laser pulse was sufficiently sharp so that its contribution to various measurements was negligible. The laser beam passed through a 30/70 beam splitter and a neutral density filter. The transmitted light went to the PMT assembly and the reflected beam was directed into a PIN diode through another neutral density filter. The PIN diode signal was used as a reference for the transit time measurement and also for triggering the oscilloscope. By observing the PIN diode output in coincidence with the PMT signal on a 500 MHz Tektronix TDS-780 digital oscilloscope, we could measure the leading edge rise time, pulse width, and the transit time of the PMT. Results are summarized in Fig. 2.

The transit time results showed good agreement with specifications. The transit times of the PMTs were in the 20 ns range at low gain. With increasing gain (voltage) the transit time values decreased to the 14 ns range (see Fig. 2, top). Transit time spread (TTS), as measured with the digital oscilloscope, was less than 2 ns for all the tubes.

Pulse width measurements showed us that the 15 ns limit set by the CMS HF requirements was not hard to reach. All the results were in the 5-8 ns range (see Fig. 2, middle).

Although almost all the PMTs were within the limits defined by the CMS HF specifications, Hamamatsu and Electron Tubes (see Fig. 2, bottom) had shorter risetimes; less than 2 ns. Photonis(XP3182/D1) PMT was right at the limit (5 ns), but the other two Photonis PMTs had risetimes longer than 5 ns.

Overall, Hamamatsu and Electron Tubes had comparable timing characteristics suitable for the HF, but Photonis did not.

4.2 Dark Current

Dark current can be caused by various processes, such as, thermionic emission from the photocathodes and the dynodes, leakage from the electrodes inside the tube or the outside connectors, and field emission current, etc. Usually, most PMTs are designed and manufactured to minimize the effects of these processes. Dark current values for the HF PMTs should be as small as possible to maximize the signal/noise ratio.

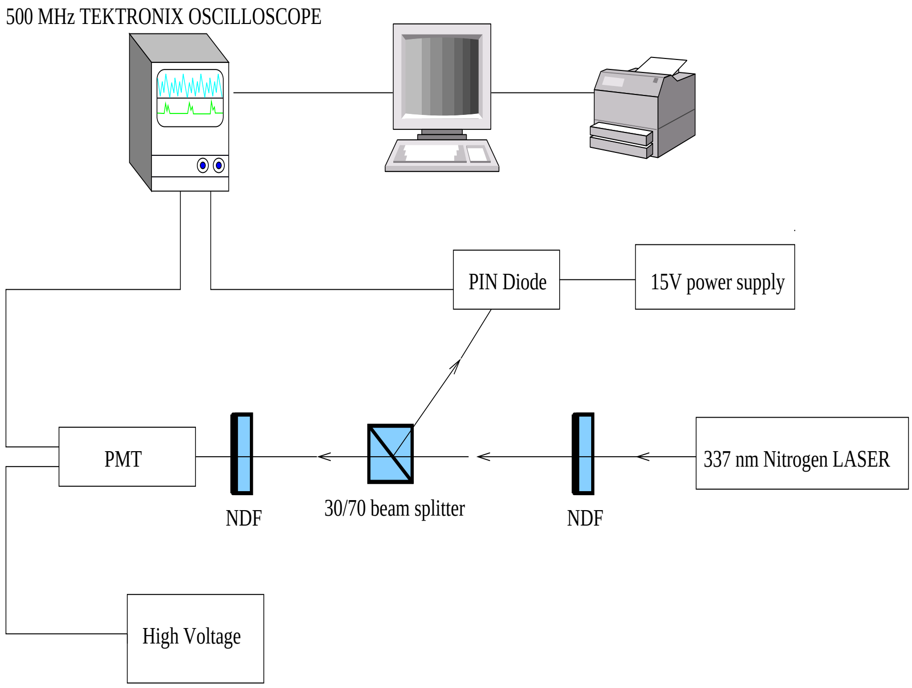

Figure 1: Test setup for timing measurements.

For dark current measurements, the PMTs were kept in a light-tight dark box for 30 minutes prior to data taking. Between the high voltage changes, we waited for the PMT output to stabilize. Dark current values were read by a picoammeter (Keithley 486).

Anode dark current measurements for almost all the PMTs were under 1nA (see Fig. 3), except for one of the Hamamatsu PMTs (ZC9957) and the Electron Tubes (D844WSB) PMT. The former was an example of the tubes that would be rejected, the latter had high dark current possibly due to its high gain. Dark current measurements were not conclusive in our comparison.

4.3 Current Gain

The HF calorimeter dynamic range requires that the gain of the PMTs should be set to low values. The expected Cherenkov light intensity generated in quartz fibers and the input requirements for the readout electronics limit the PMT gain to be adjusted to the 10^4 range. However, the PMTs should still meet the requirements set by the HF Forward Calorimeter design even if they are operated at such lower gains. Also, gain uniformity is imposed by the proposed HV distribution method. There will be 48 PMTs for each wedge in the HF calorimeter to optimize the cost. These 48 PMTs will be divided into two sets. The high voltage for each set of 24 PMTs will be provided by one HV power supply. All of the PMTs in the set should have the same gain to within a few percent.

Since the gain of a PMT is defined as: $G = I_a/I_k$, where I_a is the anode current due to a cathode photocurrent I_k, both anode and cathode currents need to be measured. For this purpose special resistive bases were manufactured for PMTs so that the current from the first dynode, i.e., the cathode current could be determined. All the dynodes and the anode were shorted together and the HV was applied between the cathode and the first dynode. A 100 kΩ resistor was added to limit the current. Anode currents were measured by using the regular resistive bases. Anode and cathode currents were corrected by subtracting the corresponding dark currents. Currents were read by the same picoammeter. A tungsten light bulb was used as a DC light source. Gain measurements were also performed in the light-tight dark box.

Gain values were expected to be similar for the candidate PMTs, because they were all 8-stage tubes, had the same cathode material, and were almost the same size except D844WSB, which was shorter than the others. The results showed that D844WSB PMT had much higher gain and quantum efficiency than the other PMTs (see Fig. 4). The other candidate tubes were within the required limits.

Both Electron Tubes PMTs resulted in cathode dark current values which were much higher than anode dark current values. The manufacturer explained this anomaly as leakage current due to the ceramic they used in the

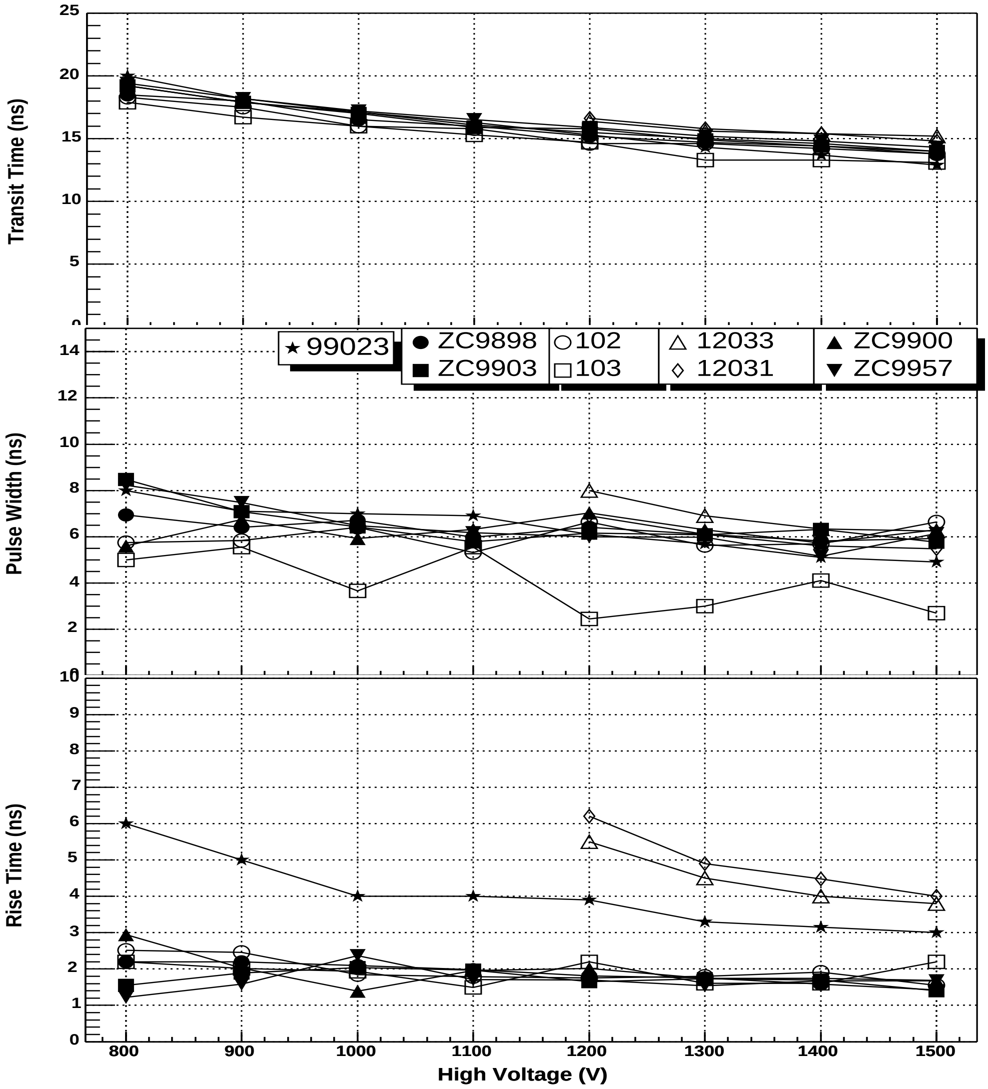

Figure 2: Timing characteristics of the candidate PMTs as a function of high voltage.

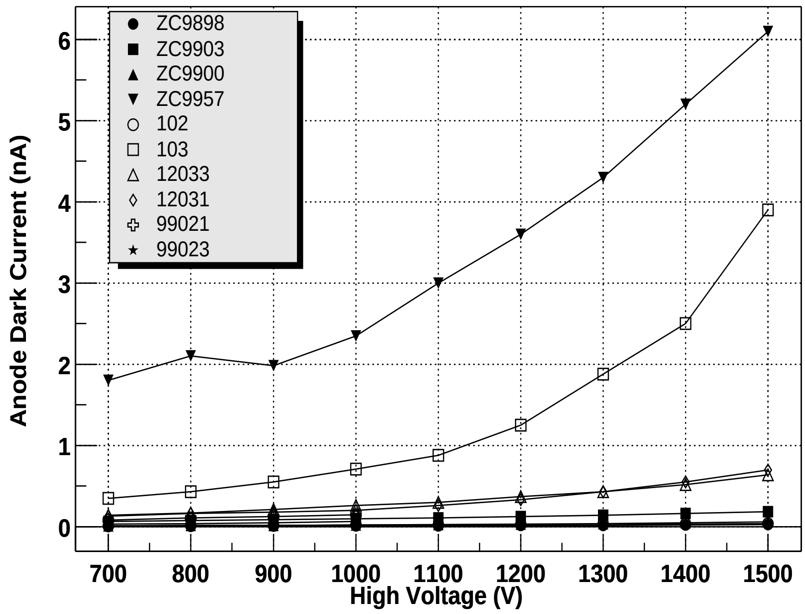

Figure 3: Anode dark current values of the candidate PMTs as a function of high voltage. Most of these results are within limits defined by the CMS HF specifications.

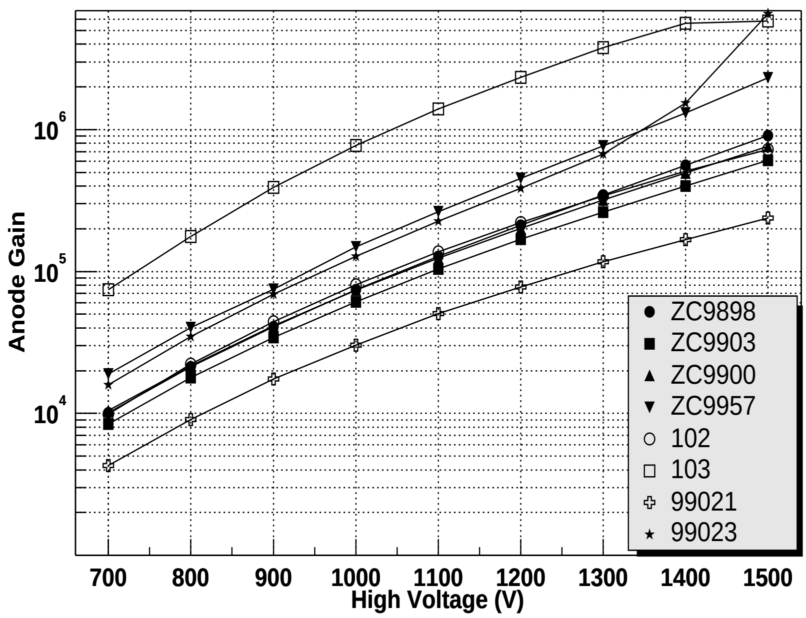

Figure 4: Gain measurements of the candidate PMTs as a function of high voltage.

PMT. All the other candidate PMTs had negligible cathode dark current values as expected. Photonis XP2960 PMT were not included in these measurements since we did not have the modified bases for them to measure the cathode current.

4.4 Single Photoelectron Spectrum (SPES)

Ideally, a photomultiplier tube should provide a constant gain at a constant voltage. However, because of the statistical nature of the electron multiplication process, there are fluctuations. Variations in the secondary emission coefficients over dynode surfaces, differences in the transit times, etc. will affect the number of electrons finally arriving at the anode due to a single electron produced in the photocathode. Resulting pulseheight distribution can be thought as the convolution of all the individual distributions due to each photoelectron. Usually the number of photoelectrons is large for typical light intensities observed and the details are washed out. On the other hand, pulseheight distribution due to a single photoelectron would be more sensitive to the fluctuations in the dynode system. This is in fact the response of the photomultiplier chain to a single electron. A single photoelectron spectrum can be obtained by shining a very low intensity light so that the probability of producing more than one photoelectron is negligible.

A Single PhotoElectron Spectrum (SPES) can be defined by several parameters. These are the mean amplitude or the centroid of the spectrum, peak to valley (P/V) ratio, and Single PhotoElectron Resolution (SPER). The centroid of the spectrum also includes those events below the single photoelectron peak in the spectrum. Some of these counts are due to the photoelectrons inelastically backscattered by the first dynode. On the other hand, SPER is calculated as the ratio of the FWHM of the peak to the peak position in the spectrum.

Single photoelectron spectrum measurements were limited to three candidate PMTs; Hamamatsu 7525HA, Electron Tubes D844WSB, and Photonis XP3182/D1, since obtaining a single photoelectron spectrum was difficult to setup and these were the best candidates from each manufacturer.

In addition to extensive timing, dark current, gain, and linearity tests, it was also very important for the candidate tubes to give reasonable resolution for single photoelectrons at the gain level of 10^4. None of the manufacturers listed SPER of their tubes in the spec sheets.

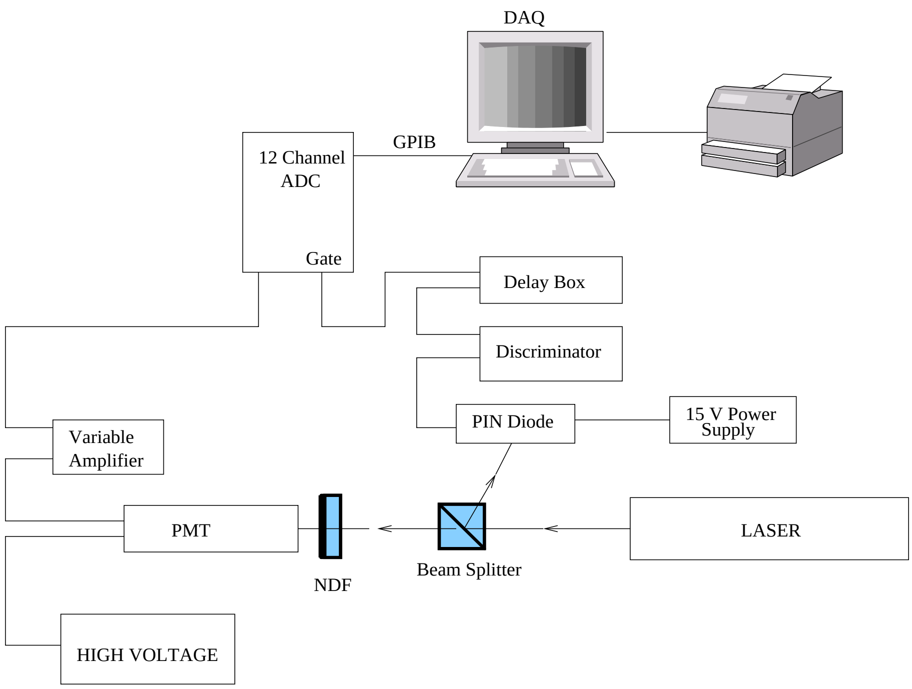

Figure 5: Block diagram of the setup for SPES measurements with ADC.

We obtained the single photoelectron spectra using the timing setup with some modifications. The digital oscilloscope was replaced with an amplifier and a charge integrating readout system. The light intensity was reduced to the level of one photon by using additional neutral density filters (Fig. 5).

Initially, a LeCroy qVt multichannel analyzer (Model 3001) was used as the charge integrating readout system.

Hamamatsu produced a spectrum with an estimated resolution slightly above 50% (FWHM/peak position) at 1500 V (10^6 gain). Electron Tubes phototube produced a spectrum with a resolution around 50% at 1200V (10^6 gain). While Electron Tubes and Hamamatsu had comparable resolutions, measurements for Photonis under the same conditions (10^6 gain) were not successful. We started with the higher tube gains (10^6) to understand the systematics in SPER measurements.

To improve the data acquisition and the S/N ratio of the system, the qVt multichannel analyzer was replaced with a LeCroy 2249A 12-channel charge sensitive ADC. The gate signal for the ADC was provided by the same PIN diode arrangement as in the previous setup (see Fig. 5).

This improved setup was used to test the Photonis and the Hamamatsu PMTs only, the latter for comparison of the setup with the qVt version. (Electron Tubes PMT was left out since it already produced a good spectrum with the qVt.) The results for the Hamamatsu were comparable with the previous measurements; a resolution slightly above 50% at 10^6 gain. The Photonis PMT again did not produce a resonable single photoelectron spectrum.

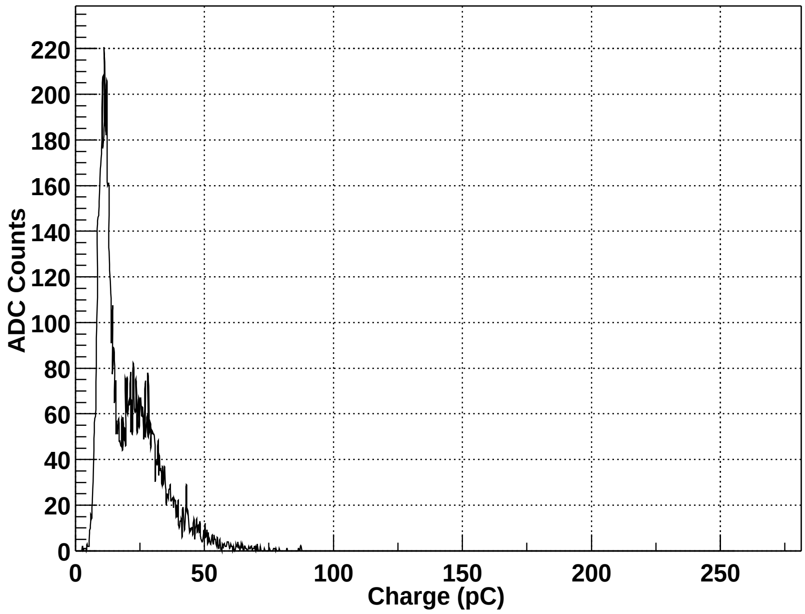

Figure 6: Single photoelectron spectrum of Hamamatsu 7525HA at 1100 V (10^4 gain).

However, it was more relevant to determine the resolutions at operating gain values. Obtaining the single photoelectron spectra at lower gains was difficult, since the signal levels were comparable to the noise level in the system. To overcome this problem, a preamplifier was placed at the base of the phototube. The preamplifier (gain=30) was manufactured in The University of Iowa CMS laboratory.

With the preamplifier, we could obtain the single photoelectron spectrum for Hamamatsu tube at 1100V (10^4 gain). This low gain measurement resulted in a resolution similar to that obtained at higher gain (see Fig. 6). However, even the improved setup could not produce a resonable spectrum for Photonis tube at 1500V (10^6 gain) (see Fig. 7).

Single photoelectron measurements provided a conclusive result at least for Photonis PMTs. While Hamamatsu and Electron Tubes had single photoelectron resolutions within the required values, the Photonis PMT could not produce a comparable single photoelectron spectrum with the same setup.

4.5 X-Y Variation of Photocathode

Uniformity of the photocathode surface is important since the individual fiber core diameters are 600 micron. Fibers attached to the same tube but coming from different sections of a tower might correspond to different charge amounts for the same light intensity if there is spatial nonuniformity. This might introduce systematic effects that would be difficult to correct for.

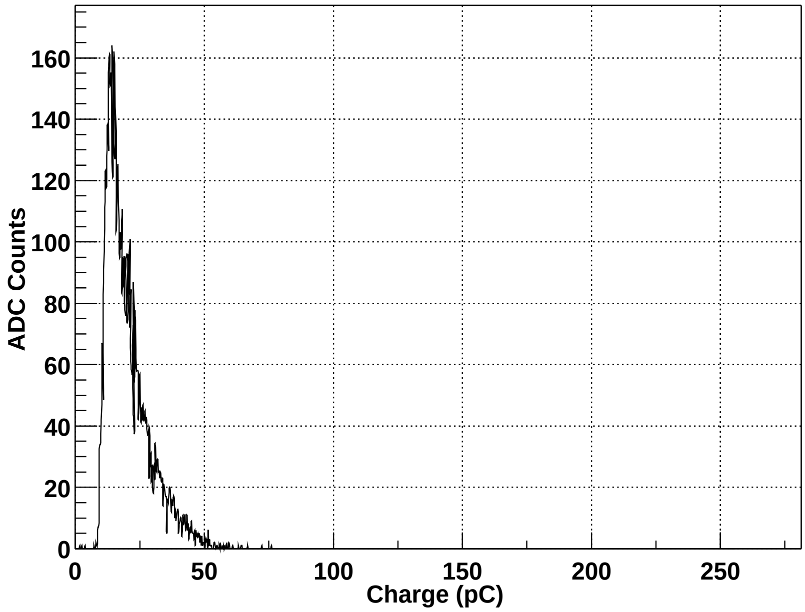

Figure 7: SPES measurement of Photonis XP3182/D1 at 1500 V (10^6 gain).

A setup is designed to scan the photocathode surface both vertically and horizontally. In this setup, light coming from a tungsten bulb shines on a mask. The mask is a completely opaque screen made of black kapton with a small (3 mm diameter) pinhole drilled into it. This mask is stationary and the PMT behind it can be moved in both vertical and horizontal directions. The PMTs are positioned so that the first dynode is horizontally oriented.

The anode current can be measured as a function of position when the PMT was being moved by the computer with the help of a stepper motor. Scan results show that the tubes meet the HF requirement for x-y uniformity. However, it turns out that the uniformity is not really that important since the fibers will not be directly attached to the tubes. There will be a 42-cm long (nominal) light guide between the fibers and the tube which mixes and disperses the light to the PMT cathode. Scans with a light guide show that any nonuniformity that might exist on the photocathode surface disappear because of the diffusion of the light beam when it reaches the photocathode surface [4].

5 Discussion and Conclusion

Some of the tests performed above provided the results necessary to compare the sample PMTs from three different manufacturers.

Tests were designed to determine whether the sample PMTs suggested by the manufacturers satisfy the operational requirements listed in Table 1. (Initial requirements, which are basically physical characteristics, listed in that table are already satisfied by the tubes suggested.) The quantities measured in these tests were transit time, pulse width, rise time, transit time spread, dark current, gain, and single photoelectron resolution. PMTs from all three manufacturers either performed within the required limits or better in most of these tests. Spatial uniformity of the photocathode surface was not a selective quantity.

However, single photoelectron resolution measurement showed a clear difference in the performance of the sample tubes. Hamamatsu R7525HA and Electron Tubes D844WSB PMTs produced single photoelectron spectra with parameters within the required limits. On the other hand, Photonis XP3182 PMTs did not produce a single photoelectron spectrum in the same setup.

Even though Electron Tubes and Hamamatsu PMTs were somewhat comparable in general, in terms of overall performance Hamamatsu PMTs performed much closer to the HF Forward Calorimeter specifications. Lower cost was also an additional point in favor of Hamamatsu PMTs

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