PERFORMANCE STUDIES OF A NEW RUSSIAN FEU115M PHOTOTUBE

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Abstract

We report on the results of tests of FEU115M one inch phototubes manufactured in Russia. The tubes are 12-stage, fast devices with high gain and low dark current. These photomultiplier tubes were developed for the PHENIX EMCal project by members of the PHENIX group at IHEP, Protvino (Russia). We report on investigations of the gain, quantum efficiency, linearity, photocathode uniformity and long-term behavior of these tubes.

I. Introduction

The main part of the electromagnetic calorimeter of the PHENIX experiment at the Relativistic Heavy Ion Collider in Brookhaven National Laboratory is a lead-scintillator sampling calorimeter with longitudinal wavelength shifting (WLS) fibers collecting the light for readout. The calorimeter consists of 15,552 towers, optically isolated from their neighbors and read out by individual phototubes. The WLS fibers from a tower form a bundle of ≈ 7 mm diameter, which is coupled via an air gap to the center of the photomultiplier tube window. The peak emission of the WLS [1] is at 490 nm, full width at 5% of the the peak emission is 470-570 nm.

A partial list of our specifications for the phototubes is as follows: quantum efficiency at 490 nm should be at least 12.5%; deviation from linear response with a tapered (B-type) base should be no more than 2% up to 40 mA peak current; rise time (10-90%) should be less than 4 ns for 10 mA into 50 Ω load; gains should be up to 2×10^6 at or below 2200 V high voltage; photocathode nonuniformity should be no worse than 10% in the central 10 mm diameter area; Long term gain changes should be less than 1%/month.

The twelve-stage, one inch diameter FEU115M phototubes are manufactured by the company MELS (Russia) [2], developed on our request, purchased and delivered to BNL by the PHENIX electromagnetic calorimeter group at the Institute for High Energy Physics (IHEP, Protvino, Russia). Further details on design and initial tests performed at IHEP may be found elsewhere [3]. These tubes were studied by a group at CEBAF as well [4]. They are our choice for high-gain, fast risetime phototubes to instrument our calorimeter, making us the first large-scale user of these tubes. At BNL we measured different performance parameters of approximately 90 such tubes (not all tubes were tested for all parameters). Also, we made long-term tests on a limited number of tubes to monitor performance variation with time and total illumination. Results of our investigations are presented in this paper.

II. Test Setup

Most of our test methods were implementations of standard techniques described in manufacturer's handbooks [5] and technical papers on high energy physics experiments [6] as well as in internal institutional notes.

Our test setup consisted of two main parts: a light generation assembly and a tube scanning assembly, both enclosed in the same dark box, but isolated mechanically. The temperature inside the box was stabilized with a system of fans at 21-22 °C and was continuously monitored.

Light was generated on an optical table with sorbothane vibration mounts to prevent accidental displacement of the sensitive optical components. We used two light sources. The first was a green HLMA-CP00 light emitting diode manufactured by Hewlett-Packard, with a peak emission at 572 nm and driven in reversed bias by a LeCroy 9210/9211 pulse generator. The light output of the LED was stable within 0.2% from pulse to pulse. The second light source was a scintillator bar interwoven by the same WLS fibers as used in the calorimeter. The scintillator was excited with a nitrogen laser (337 nm). This source delivered a spectrum identical to the one in the calorimeter where the tubes will be used. However, the pulse by pulse variations of the laser light were high, sometimes up to 10%. Therefore, the laser light was first injected into an integrating sphere and monitored at one port with a high stability, unit gain Hamamatsu R1328U-02 biplanar phototube, while the light exciting the scintillator bar was extracted from a second port with a quartz fiber. We used the signal of the biplanar tube to normalize pulse by pulse the signal from the tested tubes to eliminate effects of intensity variations.

Light from both light sources was imaged into a 600 μm distribution fiber coupled through a splitter into 7 smaller (200 μm) fibers illuminating 7 tubes at a time on the test stand. This 600 μm fiber was the only mechanical connection between the optical table and the test stand.

The tube scanning assembly consisted of a tube holder and a 3 dimensional (x, y, z) moving stage. A thin plate holding the ends of the 200 μm fibers that illuminated the individual tubes was attached to the moving stage. When moved close to the tubes, this setup enabled a fine position scan of the photocathode, while moved away from the tubes, a nearly uniform illumination of the entire surface was possible.

For the linearity tests two ORIEL remote control filter wheels and a remote control device that was able to put in or remove an additional filter were introduced into the light path.

The spectral response of the tubes was measured using a Hitachi spectrophotometer, with an absolute quantum efficiency calibration obtained with a factory calibrated Hamamatsu PIN diode.

Twelve tubes participating in the longterm exposure tests were placed in a simple tube holder in a separate box, and illuminated by a green HLMA-CP00 LED located 60 cm from the tubes. All tubes were driven with the same high voltage (2000 V). Therefore, the integrated anode current over a given time was different for each tube. The temperature inside the box was kept at 21-22 °C and the operating temperature of the bases was 45 °C.

We used two types of tapered bases, both designed by IHEP. The first one was built of discrete components, while the second was a hybrid base where the resistor chain was manufactured with thick film technology. Starting from the cathode the tapering was 3R, 2R, R, R, R, R, R, R, 1.2R, 1.6R, 2R, 3R, 3R, with typically 8 $M\Omega$ total resistance.

III. Results

The quantum efficiency (QE) of the tubes was measured with light from the laser-scintillator-WLS assembly, using light pulses of the same spectrum to which the tubes will be exposed in the calorimeter itself [7]. Therefore, our results show the operational quantum efficiency QE_{op} of the tubes in our detector. The quantity QE_{op} is the spectral response of the tube folded with the emission spectrum of the WLS. This number is more relevant for our application than the usual QE quoted at a particular wavelength and determined from the photocathode current measured in a dc charge collecting mode. In addition our method enables us to take all data with one single setup and with the base that will be actually installed into the calorimeter. On the other hand, it assumes that both the gain and the photoelectron collection efficiency are stable over a period of a few minutes. Using a factory calibrated Hamamatsu R1398 tube, QE_{op} was defined as

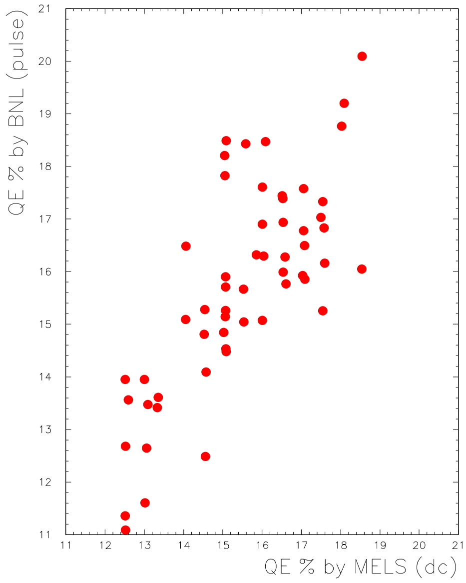

Figure 1: Quantum efficiencies measured with pulsed light and WLS light spectrum (vertical axis), compared to the quantum efficiencies measured in the factory with constant light of 500 nm wavelength.

$$QE_{op}^{test} = QE_{op}^{ref} \times \frac{N_{pe}^{test}}{N_{pe}^{ref}}$$

where QE_{op}^{test}, QE_{op}^{ref} are the operational quantum efficiencies of the tested and reference tubes, respectively, and N_{pe}^{test}, N_{pe}^{ref} are the number of photoelectrons measured by the reference and the tested tube in the same position, with the central 10 mm diameter spot illuminated. The number of photoelectrons has been calculated from the mean and Gaussian width of the signals after correcting for the pulse-by-pulse variations of light intensity. We repeatedly measured the same tubes over a period of two months and found that the values of QE_{op} were reproducible with $\sigma = 3\%$ of the absolute value of QE_{op}.

We compared our results to the quantum efficiency measured by the factory at a fixed wavelength (500 nm). The mean difference in absolute quantum efficiency between the two values was on the average only 0.2%, but had an rms of 1.3%. The results are shown in Figure 1. The average quantum efficiency was 15.5%. The sharp cutoff at 12.5% on the horizontal axis is due to the factory preselection of the tubes. Deviations between the factory values and our results seem to be consistent with the tube-to-tube variations of the spectral response shown in Figure 2, where ratios of the spectral response for 23 tubes with respect to an arbitrarily chosen tube are shown, all normalized to 1 at 500 nm wavelength.

The photocathode nonuniformity was measured with light generated by the laser-scintillator-WLS fiber assembly. The plate holding the fibers that illuminate the indi-

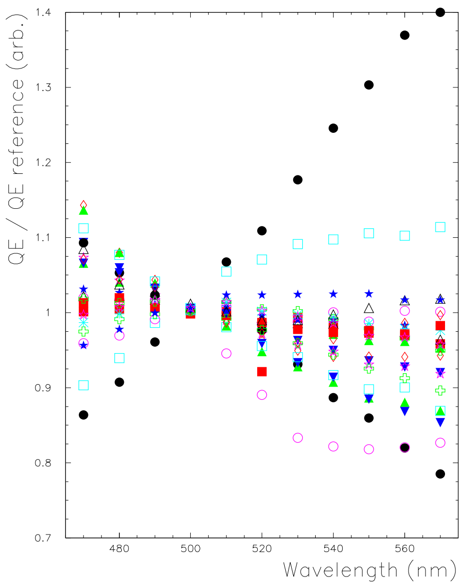

Figure 2: Variations in quantum efficiency in the region 470-570 nm. Each of 23 tubes is normalized to an arbitrarily chosen tube, and to unit quantum efficiency at 500 nm. Different shades and markers stand for different tubes.

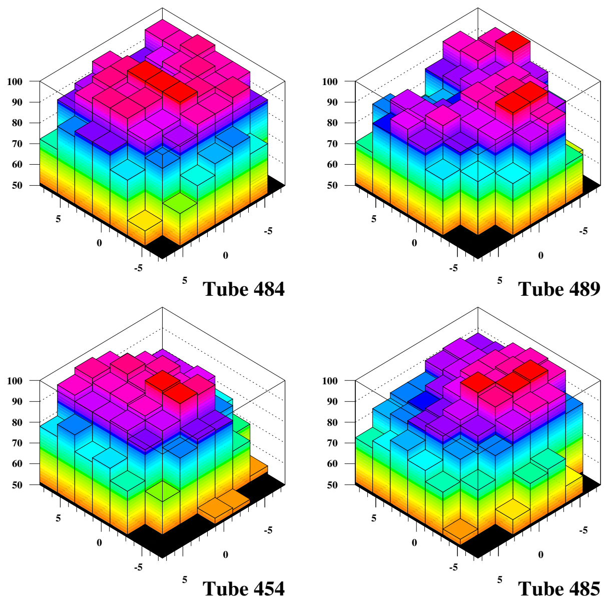

Figure 3: Photocathode nonuniformity of four randomly chosen tubes. A circle of 1.5 mm diameter is illuminated at a time. Stepsize is 2.5 mm in each direction. Points with the highest sensitivity are normalized to 100 on this plot.

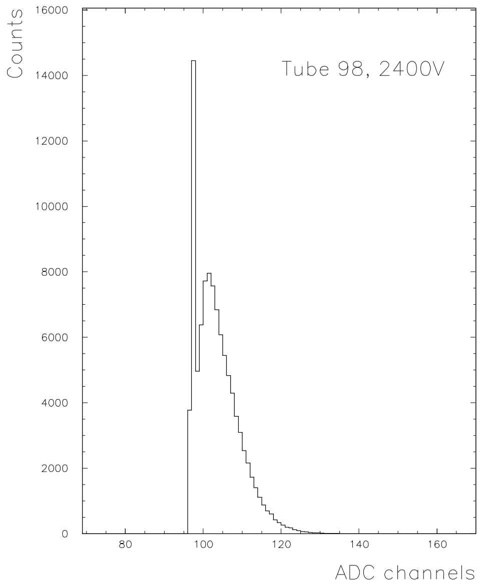

Figure 4: Typical single photoelectron peak, measured with a discrete base in a .25 pC/channel LeCroy 2249W ADC. The gain is $\approx 6 \times 10^6$ at 2400 V.

vidual tubes was moved close to the tubes such that only a $\approx$ 1.5 mm diameter area was exposed to direct light. (A small fraction of the light illuminated the surrounding area via multiple reflection.) We scanned the surface of the photocathode in both directions in 2.5 mm steps. At each point the number of photoelectrons was calculated, then normalized to 100 at the highest sensitivity point. The results are shown in Figure 3. Clearly, the photocathodes are not uniform in the region scanned, and also, the region with the highest sensitivity is not always in the center. However, they fulfilled our specification, that the variation in the central 10 mm spot should be less than 10%. It should be noted that our results on photocathode nonuniformity are not in contradiction with the reproducibility of the quantum efficiency measurement, since mechanical constraints in our setup ensured that the tubes were always installed with the same orientation into the tube holder.

Single photoelectron peaks were clearly visible in a .25 pC/channel LeCroy 2249W ADC for 20 out of 22 tubes. This measurement was done by decreasing the amplitude of the pulse driving the LED in reversed bias. A typical spectrum is shown on Figure 4. Note that 4 channels above pedestal corresponds to a gain of 6×10^6, three times higher than our specification. The anode dark currents, measured with a Keithley picoammeter, were typically less than 3 nA at 2000 V.

Gains were measured using the LED light source and varying the high voltage on the tubes between 1700 V and 2200 V. The gain was calculated from a Gaussian fit

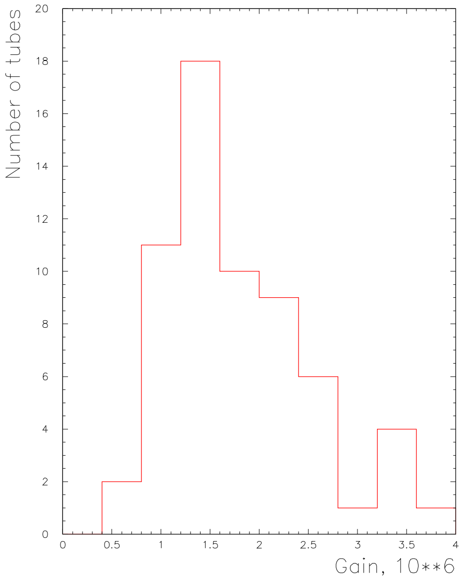

Figure 5: Distribution of gains at a fixed high voltage (2000 V).

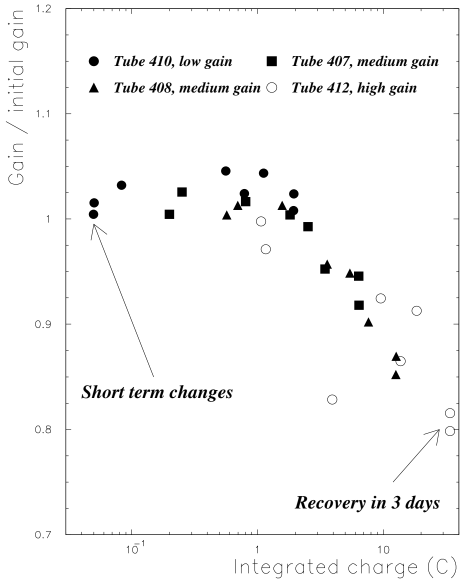

Figure 6: Gain/initial gain vs. integrated anode current for four tubes. For every tube the first two points (lowest charges) were measured on two consecutive days, indicating short term changes. For every tube there are two points for the highest charge, the second showing the gain after three days without exposure to light (recovery).

to the pedestal subtracted peak as

$$g = \frac{0.25[pC/chan]}{1.6\times10^{-19}[C/e]}\frac{\sigma^2}{mean}$$

For each tube, the amount of light was varied until the number of photoelectrons was between 100 and 200. We found that this condition minimizes the error on the measurement, which was kept below 2%. The gains of the tubes at a fixed voltage varied by a factor of 3, and the mean value was 1.7×10^6 at 2000 V. The data are shown in Figure 5. When the gain curves of the tubes were fitted with a function $g = a + bV^c$, the average exponent was $c = 9.6$.

The long term behavior of 12 tubes is illustrated in Figure 6. As mentioned before, in this test, the high voltage for all tubes was set to 2000 V. The tubes were in a separate test box, illuminated by a single LED. Initially the pulse rate was 1.5 kHz, which was later changed to 5 kHz after most tubes were exposed to ≈ 1 Coulomb (C) integrated anode current. Due to differences in gain the total charge varied from tube to tube. Figure 6 shows gains of four tubes after an exposure to a certain integrated anode current, divided by the initial gain of the tubes, and plotted as a function of the integrated anode current. There is no significant gain loss (more than 10%) before the total charge reaches 10 C. Note that the expected total charge exposure in our application is less than 1.0 C/year even for the highest design luminosity and intensive monitoring. The first point on the plot (lowest charge) was taken after an initial exposure to the light and it was normalized to 1 in order to make the data comparable. The second measurement was taken 24 hours after the first one. Therefore, differences between the first two points indicate the short term stability. Also, at the very end of the test, the tubes were kept for three days in the dark box with the high voltage turned on, but without further exposure to the LED light, and then once again the gains were measured. All tubes exhibited some gain recovery.

To preserve clarity on Figure 6 we show only part of our results to indicate different trends. The majority of the tubes omitted from the plot remained in the central band, around 1, *i.e.* their gains did not change before reaching 10 C integrated current. The precision of the gain measurement was better than 3%.

Linearity was measured with the LED, driven by a high amplitude pulse. The amplitude (and the amount of light generated) was constant throughout the measurement. The light was attenuated in 25 steps over two orders of magnitude by neutral density filters in two ORIEL filter wheels. For any given light level, the amplitude of the signal in the tube was measured (A_{full}), then an auxiliary filter was inserted, reducing the light by a factor of two (A_{half}). All filters were placed at an angle with respect to each other to avoid multiple reflections that distort the measurement, particularly at low intensities (high attenuation). The nonlinearity was defined as the change (in percentage) of the ratio A_{full}/A_{half}, and is plotted on Figure 7 as a function of the peak current corresponding to A_{full}. All tubes were measured with the same discrete

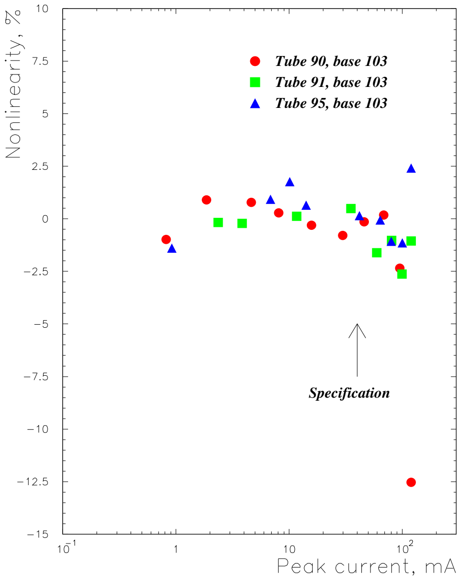

Figure 7: Nonlinearity of three tubes as a function of peak current measured with the same tapered base built of discrete elements.

base. Therefore, the results indicate differences between tubes. However, all tested tubes fulfilled our requirement of less than 2% nonlinearity up to 40 mA peak current.

We found that despite careful handling, four tubes lost vacuum because of small cracks that developed where the pins enter the body of the tube. According to recent information the factory took corrective actions with respect to this problem.

IV. Summary

We have tested a large sample of Russian FEU115M 12-stage, high-gain, fast phototubes. These tubes were preselected in the factory. We found that the overall performance of the tubes was satisfactory and in accordance with our specifications.

The useful gains were at least $4-6\times10^6$, three times higher than our specification. Nonlinearity was smaller than 2% up to 80 mA peak current. Integrated anode charges up to 10 C did not change the gain considerably for the majority of the tubes. The average quantum efficiency was 15.5% at 500 nm, slightly higher when measured with the WLS spectrum (470 to 570 nm). Spectral response varied typically 10% from tube to tube. The photocathode nonuniformity was less than 10% in the central 10 mm of the tube, although the most sensitive spot was not always in the center.

Acknowledgement

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References

[1] Bicron BCF99-29B

[2] MELS, Electrozavodskaya Ul. 23, I05023, Moscow, Russia

[3] V Rykalin *et al.* submitted to Nuclear Instruments and Methods

[4] S. Majewski, R. Wojcik, D. Weisenberger: Studies of a FEU-115M Photomultiplier, CEBAF Note, June 12, 1993, not published

[5] *E.g.* Photomultiplier Handbook, Burle Industries, 1989; Photomultiplier Tube: Principle to Application, Hamamatsu Photonics, 1994

[6] *E.g.* T. Devlin *et al.*: Phototube testing for CDF, Nuclear Instruments and Methods, A268 (1988) 24; T. Ishii *et al.*: Automatic test of photomultiplier tubes for the ZEUS forward and rear calorimeters, Nuclear Instruments and Methods, A320 (1992) 449.

[7] This is not the usual method of measuring quantum efficiency. However, we will show that our results are usually in good correlation with measurements at a fixed wavelength and with constant light (DC), and deviations between the two measurements are consistent with differences in the spectral response of the tubes.