Available on CMS information server **CMS IN 2005/009**

CMS Internal Note

March, 2005

Spatial efficiency of the CMS Vacuum Phototriodes

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Abstract

Specially developed vacuum phototriodes (VPTs) will be used to detect scintillation light produced in the lead tungstate ($PbWO_4$) crystals in the end-cap sub-system of the electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid (CMS) detector. The spatial uniformity of the VPT's photocathode quantum efficiency was measured by scanning their photosensitive area with a collimated light source.

1 Introduction

The operating conditions in CMS, at the Large Hadron Collider (LHC), require dedicated photodetectors for the barrel and endcap parts of the CMS electromagnetic calorimeter (ECAL) [1]. In close collaboration with industry CMS has developed special photodetectors for the ECAL readout. Avalanche photodiodes (APDs) were developed in collaboration with Hamamatsu Photonics for the ECAL barrel. They are described in detail elsewhere [2]. However, APDs cannot be used in the endcaps since the radiation levels, and in particular the neutron fluence, are much higher than in the barrel. These levels would give rise to unacceptably high leakage currents [1]. A uniform 4 T axial magnetic field in CMS prevents the use of standard photomultiplier tubes (PMs) in the endcaps. Vacuum phototriodes, which are essentially single stage photomultiplier tubes, have been chosen since they are radiation tolerant and provide a gain of ~10 for tube orientations to the field from 0 - 30 degrees, the range subtended in the endcaps.

2 CMS Vacuum Phototriodes

Vacuum phototriodes (VPTs) were developed in collaboration with Research Institute Electron (RIE) in St. Petersburg, Russia. A detailed description of the VPT characteristics can be found elsewhere [3]. Both photodetectors (VPTs and APDs) have an internal gain and an optimized area to cope with the modest light yield of the $PbWO_4$ crystal. VPTs with an external diameter of 25.4 mm have about the same order of total efficiency (quantum efficiency × sensitive photocathode area) for the detection of $PbWO_4$ light as 50 mm^2 APDs with several times higher quantum efficiency. Measurements of the spatial uniformity of APD quantum efficiencies and gains are given in [4].

Figure 1 illustrates schematically the VPT construction (left) and shows a photograph of a VPT (right). A planar, bialkali, semitransparent photocathode is deposited on the inner surface of glass faceplate. The anode is a fine metallic mesh located between the photocathode and the dynode. The dynode is solid metal coated with the same material as the photocathode. In operation the photocathode is grounded, the dynode is at V_D= 800 V to ensure a high electron secondary emission factor, and the anode voltage is approximately 200 V higher (V_A=1000 V) to optimise the collection of secondary electrons emitted by the dynode [3]. The photocathode quantum efficiency at 420 nm under uniform illumination (average over photocathode area) is about 20% [5].

Although the $PbWO_4$ crystal scintillation light will uniformly illuminate the VPT faceplate, and each channel will be individually calibrated, it is important to monitor the spatial distribution of the photocathode quantum efficiency during VPT mass production. A pronounced spatial non-uniformity in VPT quantum efficiency, in combination with a magnetic field which is not parallel to the tube axis, may cause a significant fraction of the electrons generated from the remaining photocathode area to be lost to the wall of the glass envelope before reaching the electrodes. This would cause a larger than expected decrease in VPT response, an increase in the energy equivalent noise term for that channel and poorer photo-statistics. Significant spatial non-uniformities could also be indicative of poor tube fabrication bringing with it the associated risk of high voltage breakdown.

All mass production VPTs are visually inspected at the Rutherford Appleton Laboratory (RAL) for photocathode spatial uniformity upon receipt from the producer. The majority of VPTs are produced with photocathodes which appear uniform under visual inspection. However, approximately two percent of VPTs have faceplates that appear to have missing photocathode regions, usually crescent shaped, at the edge of the faceplate and involving up to 10% of the faceplate surface area. A further two percent have up to 40% missing. In order to confirm that these visual observations correspond to regions of lower quantum efficiency, measurements of the spatial uniformity of VPT photo-cathodes were performed at the Technical University of Split.

Measurements of the photocurrent, as a function of the position of a collimated light source across the VPT photocathode, are used to quantify the level of (non)uniformity and provide information about the quality and stability of the VPT production process.

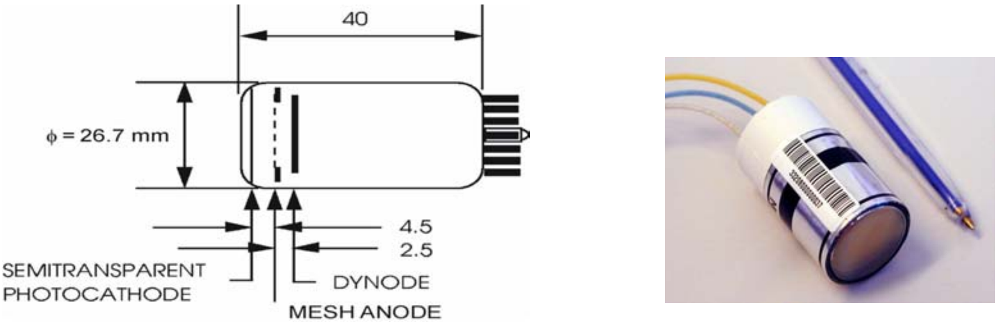

Figure 1. A schematic view of a vacuum phototriode (left) and photograph of a typical VPT (right)

3 The setup for uniformity measurements

A photograph of the setup for VPT uniformity measurements at Technical University of Split is shown in Figure 2. The setup consists of a moveable table with two degrees of freedom, each with a maximum range of 25 mm. Stepper motors are mounted on micrometer screws which move the table along two perpendicular directions. Specially developed LabView based software, via a parallel port, controls the stepper motors. LED light is transported by an optical fiber to the VPT photocathode. The fibre is supported on a mount on the moveable table. The VPT is fixed and the collimated light spot scans across its faceplate. The LabView software provides different scanning procedures. The step size can be changed by multiples of 2.5μm. A voltage source (ORTEC 451) was used for the VPT bias. The photocurrent was measured as a voltage drop across a 1MΩ resistor (0.1% precision) in series with the photocathode, using a Multimeter Keithley 2000. The same software which controls the moveable table, via an RS232 port, reads out the multimeter, and through another RS232 port, the temperature using a PT100 temperature probe (Pico Technology 0.1 ^{o}C precision).

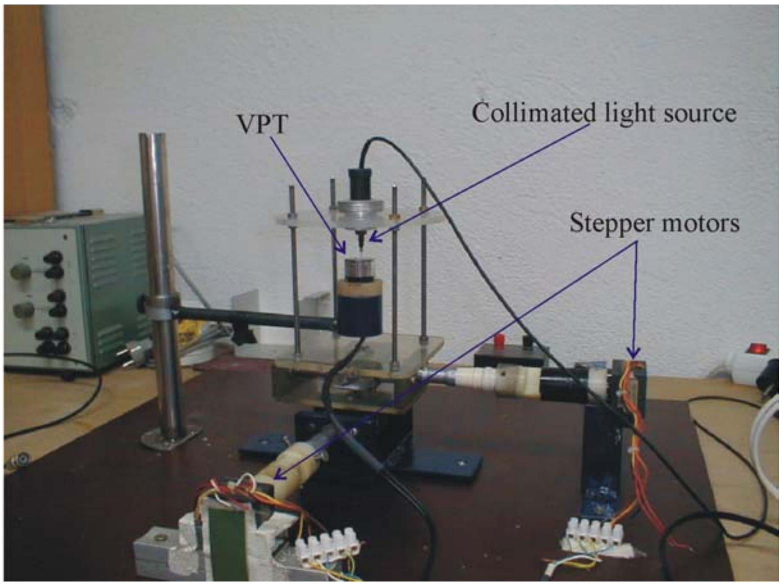

Figure 2. Photograph of the setup for measurements of the VPT uniformity.

4 Spatial efficiency of the VPT photocathode

The measurement of the VPT photocathode spatial efficiency is performed by operating the VPTs in diode mode (no gain). The photocathode is held at ground and the anode and dynode are operated at V_{AD} = 250 V. The photocurrent is calculated from the measured voltage drop across 1 MΩ resistor in series with photocathode. The light spot, of 500μm diameter, provided by a blue LED with an emission peak at 430 nm, scans the VPT faceplate. Four VPTs (one good (137), three bad (354, 864, 728), under visual inspection) have been scanned to evaluate whether the observations from the visual inspection were correlated with non-uniformity in photocathode efficiency across the faceplate.

The quantum efficiency and gain for each VPT are listed in Table 1. The measurements were undertaken by the manufacturer at B=0T. Also listed in Table 1 is the VPT yield (ADC counts, arbitrary scale) measured at the Rutherford Appleton Laboratory at B=0T, normalised to the gain times quantum efficiency quality factor, and the percent of missing photocathode area estimated by visual inspection.

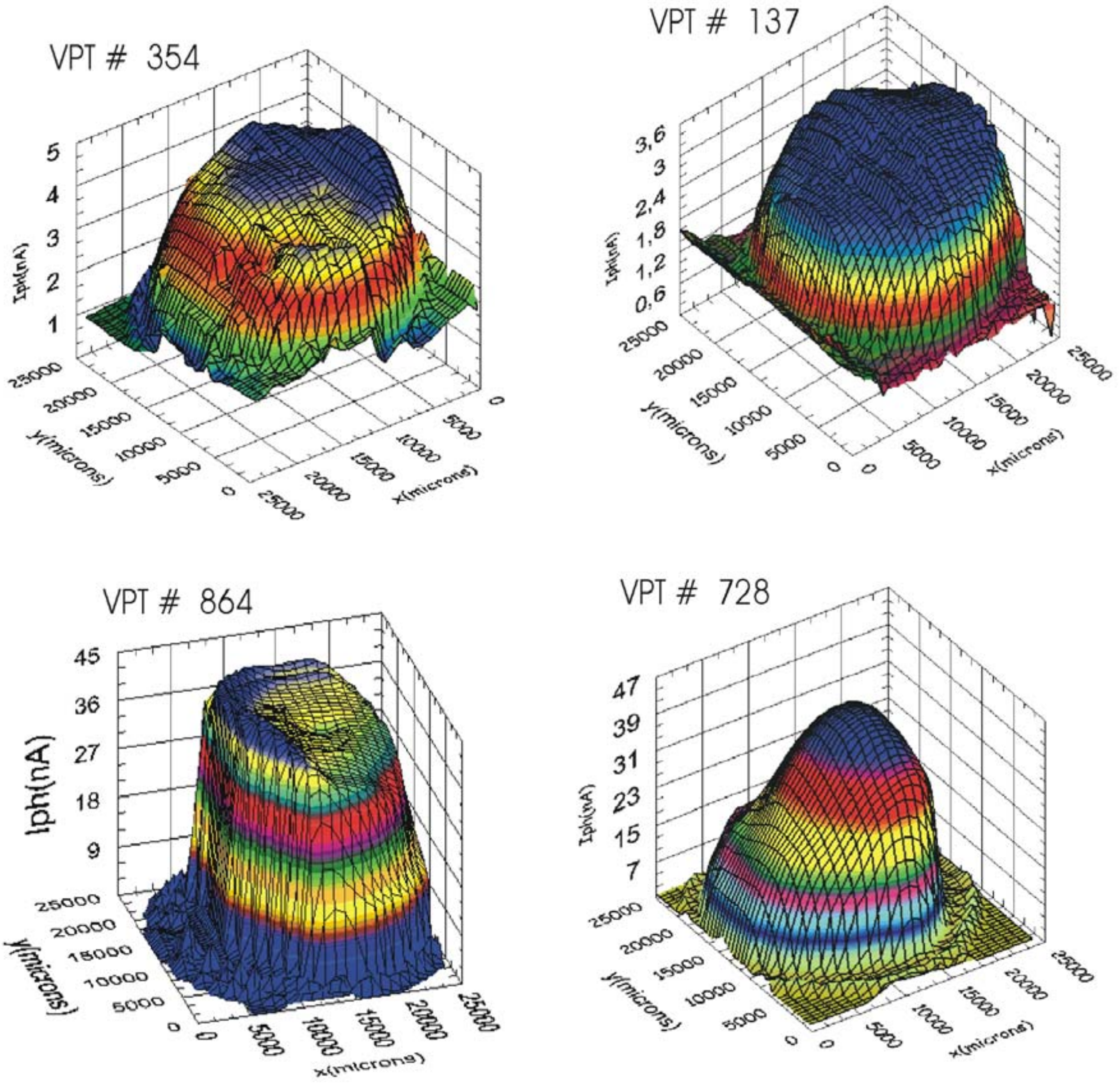

Figure 3. Photocathode efficiency scans in steps of 500 microns with a light spot of 500 microns provided by a blue LED with a peak emission at 430 nm, for VPTs 354, 137, 864 and 728.

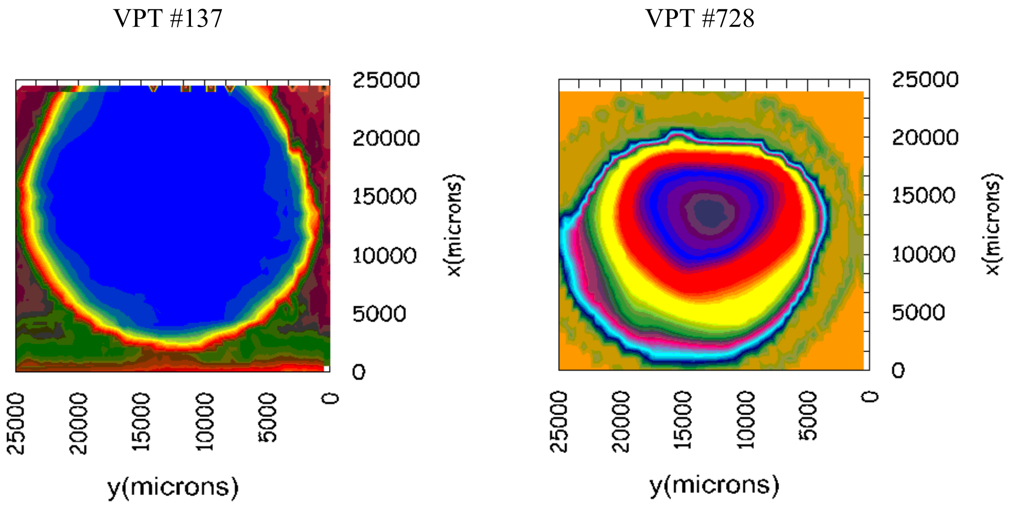

Figure 4. Photocathode efficiency scans in steps of 500 microns with a light spot of 500 microns provided by a blue LED with a peak emission at 430 nm, left VPT 137, right VPT 728.

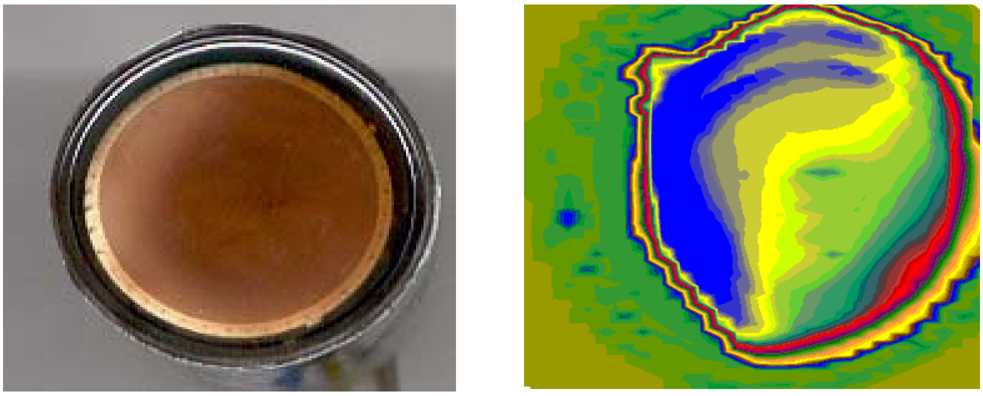

Figure 5. A photograph of the faceplate of VPT 864 (left), and the measured spatial efficiency with a light spot of 500 microns scanned across the faceplate of VPT 864 (right).

Visual inspection is a subjective exercise and the missing photocathode area is estimated to ~30-50% precision for missing areas of 20% or less. The inspection is principally carried out by one experienced operator and all visual inspection results are logged in a database.

Most VPTs measured at RAL have a normalised yield of between 11 and 16. VPT 354 is lower than expected. VPT 728 is below average, as is VPT 137 which is visually normal. VPT 864 has a normalised yield that is much higher than normal tubes – this could indicate a soft tube, containing unwanted gas inside, giving anomalously high gain and the potential risk of breakdown in the future.

The results of photocathode efficiency scans are shown in Figure 3. In Figure 4 the same data for VPT 137 and VPT 728 are presented as contour plots to emphasize the difference between VPT 137 with a high level of uniformity and VPT 728 with a very low level of uniformity.

The shape of the faceplate (non)uniformity measured by the light spot scan has the same shape as seen under visual inspection as shown in Figure 5. The distributions of the photocurrents coming from the photosensitive region (22 mm diameter) are shown in Figure 6.

The level of (non)uniformity, defined as the fractional r.m.s. of the photocurrent distribution, is given in Table 1.

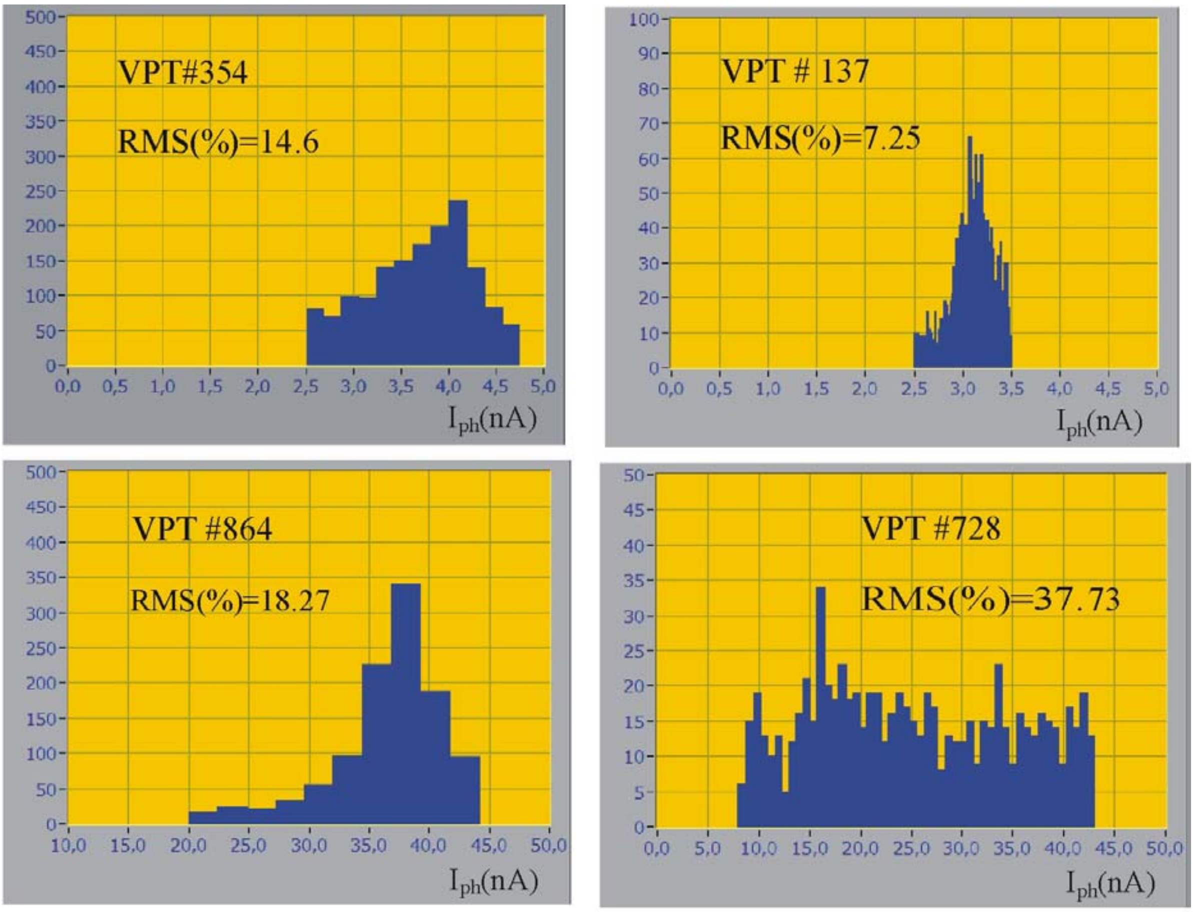

Figure 6. The distributions of the photocurrents measured across the photosensitive area of the VPT faceplates, for VPTs 354, 137, 864 and 728.

VPT BARCODE	Q.E.	GAIN	YIELD (B=0T) / (GAIN * Q.E.)	MISSING PHOTOCATHODE (visual inspection)	$\frac{\sigma_{\bar{I}_{ph}}}{\bar{I}_{ph}}$ (%)
137	20.9	8	10.8	0 %	7.25
354	18.6	11.4	8.3	20 %	14.6
864	21	7.6	25.1	25 %	18.27
728	25	8.3	11.7	40 %	37.73

Table 1. The quantum efficiency and gain measured by the producer and the normalised yield, at B=0T, measured at RAL, the percentage of missing photocathode area estimated by visual inspection and the spatial (non)uniformity of VPT photocathode measured by the light spot scan at Split.

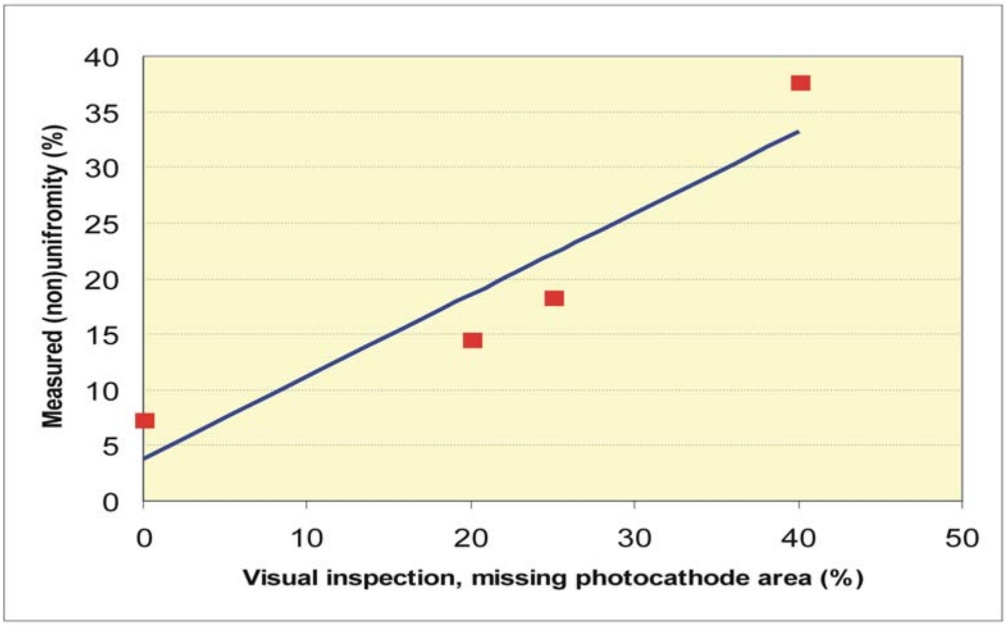

Figure 7. The correlation between the "missing" photocathode region under visual inspection and the measured (non)uniformity by the collimated light spot scan across the photocathode. The line is a linear fit to the data points (squares).

The measured level of the spatial efficiency of the VPT photocathode is correlated with the "missing" photocathode region estimated by visual inspection as shown in Figure 7. The measurements demonstrate that the non-uniformities seen during the visual inspection of VPTs are correlated with non-uniform quantum efficiency.

5 Conclusion

Visual inspection will be used to reject those VPTs where the spatial non-uniformity of the photocathode is greater than 20%. These VPTs will not be used in CMS due to the risk that their response might change markedly in a magnetic field or that they might be susceptible to breakdown.

References

[1] **CMS Collaboration,** The electromagnetic calorimeter project, *Technical Design Report, CERN/LHC 97-33, December 1997.*

[2] **K. Deiters et al,** *Nucl. Instrum. Meth. A442 (2000) 193.*

[3] **B. Brown et al,** *Nucl. Instrum. Meth.A469 (2001) 29.*

[4] **N. Godinovic et al.**, Uniformity Measurements Across the area of CMS ECAL Avalanche Photodiode, *CMS Note 2004/01.8*

[5] **K. W. Bell et al,** Vacuum Phototriodes for the CMS Electromagnetic Calorimeter Endcap, *IEEE Trans.Nucl.Sci.51:2284-2287,2004.*