4.2 Vacuum Phototriodes

4.2.1 Introduction

The photodetectors for the Electromagnetic Calorimeter Endcaps, covering the rapidity range $1.5 \leq |\eta| \leq 3.0$, are required to operate in a 4 T magnetic field, should survive radiation exposures up to 2 Mrad/year and must offer an adequate signal-to-noise ratio with the low light yield of $PbWO_4$ crystals. The 5 mm-diameter APDs proposed for use in the barrel ECAL are practically insensitive to magnetic field, provide gain in the region of 50 and offer satisfactory signal/noise performance. However, they are insufficiently radiation hard for use over the whole rapidity range covered by the forward ECAL.

Fine-mesh photomultipliers with low gain, such as phototriodes or phototetrodes, are promising candidate photodetectors for the ECAL endcaps. Vacuum phototriodes with a diameter of 75 mm, situated in an 0.4 T axial magnetic field, have been successfully employed to detect Cerenkov light produced by electromagnetic showers in lead-glass blocks in the OPAL endcaps [4.13]. Hamamatsu 25 mm diameter phototetrodes used in the DELPHI STIC calorimeter, have been tested in fields up to 4 T and proved to have an acceptable gain (7-9) at 4 T [4.14]. Hamamatsu manufacture 25 mm diameter phototriodes and phototetrodes with about the same total efficiency for light detection as 5 mm-diameter APDs. In zero magnetic field, phototetrodes provide a gain of about 30 and phototriodes about 12, with superior noise performance to APDs. In a 4 T quasi-axial magnetic field the gain of the phototetrode falls by a factor of 4-6 and that of the triode by a factor of about 2, see Fig. 4.18.

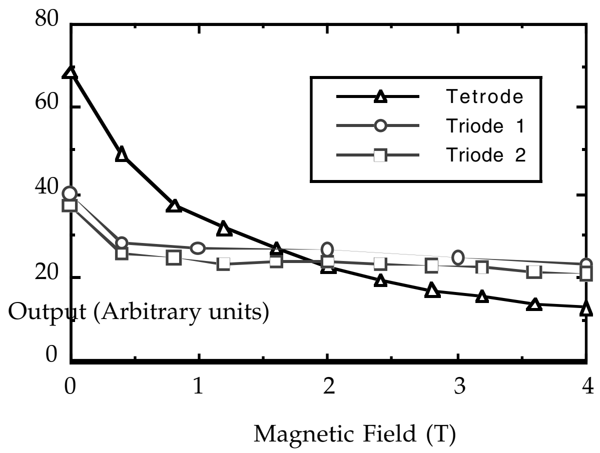

Fig. 4.18: Gain -v- Magnetic field for two Hamamatsu 1" phototriodes and a phototetrode. Field at tilt angle of 15° to tube axis.

The gain of the Hamamatsu triode falls rapidly below 1 T, but declines only slowly thereafter, offering the possibility that devices could be tested initially in a magnetic field of 2 T or less and their behaviour at 4 T inferred, thus obviating the need to measure all endcap photodetectors in the higher field. Triodes are also expected to be cheaper than tetrodes.

The Research Institute Electron, (RIE), St. Petersburg, Russia, and the Moscow Factory MELZ, in collaboration with Petersburg Nuclear Physics Institute, (PNPI), have been undertaking research on the design and construction of fine-mesh phototubes, both of high gain, (10^5 – 10^6), and low gain, (phototetrodes and photodiodes), with external diameters of 20 and 30 mm, since 1995. The dependence of relative gain on magnetic field of the RIE tetrode and triode at two tilt angles to the field is shown in Fig. 4.19.

Fig. 4.19: Relative gain –v- magnetic field for a RIE phototetrode and photodiode at two tilt angles to the magnetic field.

Prototype 22-mm diameter vacuum phototriodes produced by Electron Tubes Ltd, Ruislip, England are currently being tested by several UK groups. The choice of tube diameter depends on the cross section of the larger end of the PWO crystal, currently limited to $25.9 \times 25.9\ \mathrm{mm}^2$ by the boule size, and the space required for mechanical support of the crystal. An external diameter of 22 mm appears to be the maximum that can be accommodated with a circular photodetector.

4.2.2 Device parameters

Figure 4.20 illustrates the construction of a typical phototriode.

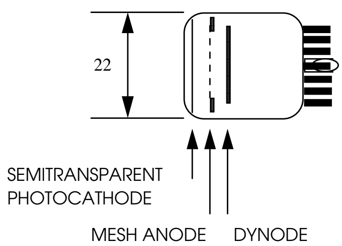

Fig. 4.20: Electrode layout of a typical vacuum phototriode.

A planar, semitransparent photocathode is deposited on the inner surface of the faceplate, which, for long-term operation in a high radiation environment, must be made from radiationresistant glass. A mesh anode is situated 4-5 mm from the photocathode and a reflective dynode is deposited on a planar electrode a similar distance, or less (2-3 mm), downstream of the anode. Typically, the photocathode is grounded, the anode is operated at about 1000 V and the dynode at about 500 V. Most photoelectrons liberated from the photocathode pass through the anode mesh and impact on the dynode, producing secondary electrons which are attracted to the anode mesh, where a large fraction is captured.

Phototetrodes have a similar structure, but have a second grid. In this case both grids may be used as dynodes, with the planar electrode biased as anode, or the functions of the second grid and planar electrode may be reversed so that the second grid acts as anode. There is no significant difference between the two modes of operation.

Figure 4.21 compares typical quantum efficiencies obtained with multialkali photocathodes in 20 mm fine-mesh phototriodes from RIE, St. Petersburg, and 25 mm tetrodes from Hamamatsu.

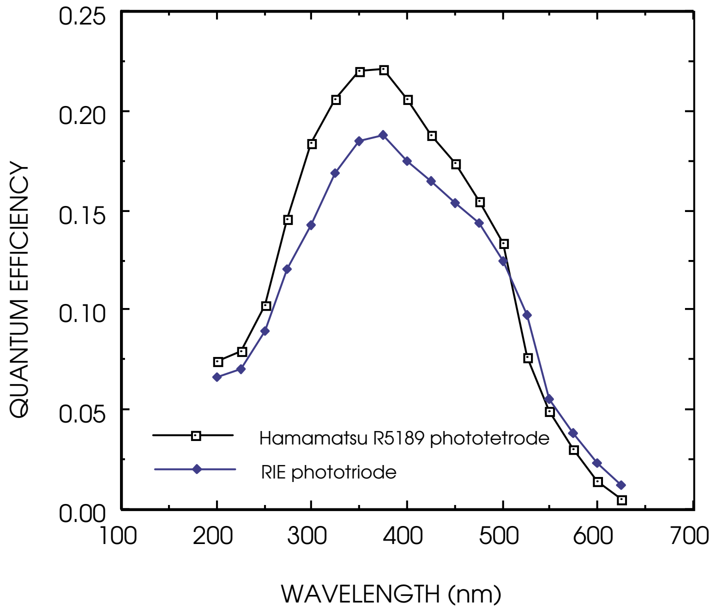

Fig. 4.21: Measured photocathode quantum efficiencies -v- wavelength for a Hamamatsu R5189 tetrode and a RIE triode.

A direct comparison of the response of a Hamamatsu and a RIE phototetrode illuminated by LED pulses of differing wavelength is shown in Table 4.6. In the region of the emission peak of $PbWO_4$ the response differs by only 20-30%.

Table 4.6: Relative response of Hamamatsu R5189 and RIE FEU-188 phototetrodes as a function of LED colour

LED colour	Red	Green	Blue
Pulse height ratio (Hamamatsu/RIE)	0.58	1.18	1.29

When vacuum photodetectors are used in a strong magnetic field the electrons spiral around the field lines, with radii of curvature in the micron range. In order to minimise electron loss in non-axial fields the axial separation of the electrodes should be kept small, consistent with the need to use operating voltages of the order of kV. A fine mesh is essential to capture spiralling electrons efficiently. Hamamatsu phototriodes typically employ 30 line per mm grids with a transparency of about 72%. Prototypes from RIE have used 30 l/mm meshes, as well as 60 and 100 l/mm. The 'magnetic hardness', - the ratio of the gain in a 4T axial magnetic field to the gain at zero field is lower in the case of 30 l/mm grids: 0.60 with 30 l/mm, 0.78 with 60 l/mm and 0.82 with 100 l/mm. Measurements are performed over a range of magnetic fields from zero to 4 T. The gain increases as the tilt angle of the field is varied from 0 to 45 deg., see Fig. 4.22a and 4.22b. The effect depends on the value of the magnetic field, see Ref. [4.15]. The change in gain with tilt angle may be due to an increase in the effective area of grid bars as the tilt angle increases. A mesh of 30 l/mm seems the most promising choice, because, in the tilt angle range 18-30 deg., corresponding to the endcap rapidity range 1.5–3.0, it is easier to obtain an adequate gain at 4 T.

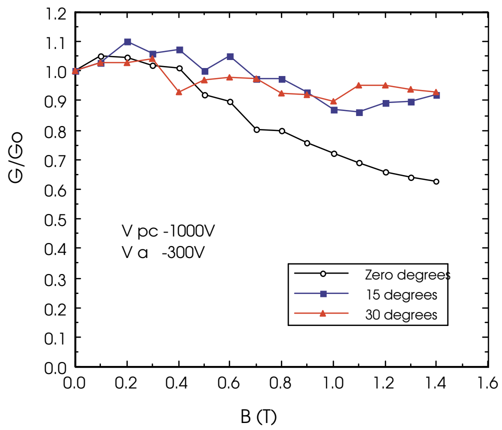

Fig. 4.22a: Relative gain -v- magnetic field of a 30 l/mm RIE phototriode.

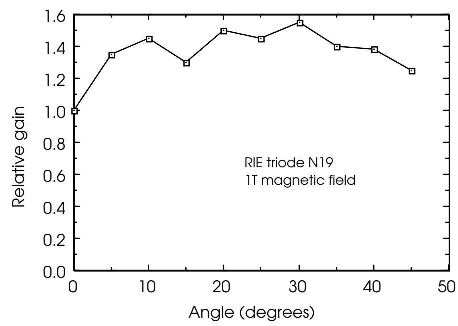

Fig. 4.22b: Relative gain -v- tilt angle of a RIE phototriode in a 1T magnetic field.

Figure 4.23 illustrates the angular dependence of the output of Hamamatsu 1" phototriodes and phototetrodes in a 4T magnetic field.

Computer modelling of the field dependence indicates a possible change in gain as the tube is rotated about its axis, for a non-axial orientation of the magnetic field, but there is, as yet, no experimental evidence to support this result.

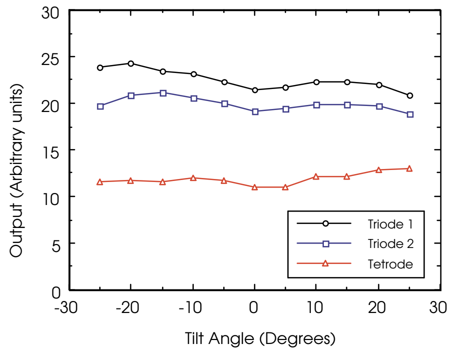

Fig. 4.23: Relative output -v- tilt angle for Hamamatsu 1" phototriodes and a phototetrode in a 4 T magnetic field.

4.2.3 Radiation hardness

The principal effect of high-energy radiation on standard commercial photomultipliers is the darkening of the faceplate due to the generation of colour centres in the material. Quartz is extremely radiation hard, but quartz-window tubes are expensive and bulky, because of the need to make a graded seal between the quartz faceplate and the borosilicate glass of the envelope. A number of radiation-hard glasses are available commercially. RIE tubes will be provided with faceplates of C96-1 radiation-hard glass. The optical transmission curves for a 1mm thick sample of this glass after a number of different doses of ^{60}Co radiation are shown in Fig. 4.24.

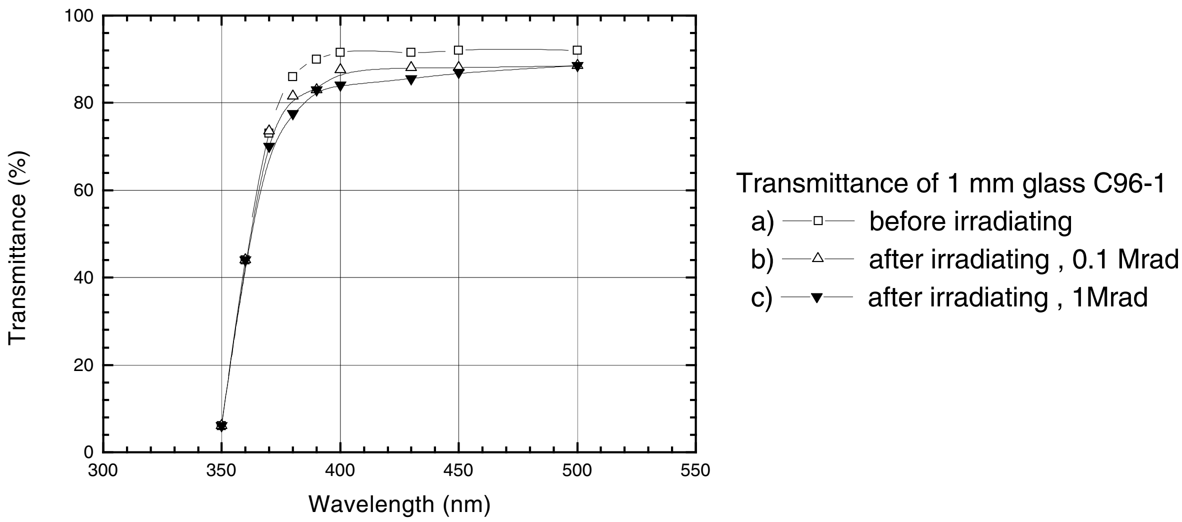

Fig. 4.24: Optical transmission curves for C96-1 radiation-hard glass following ^{60}Co radiation.

The change in transmission of this glass following an exposure to a reactor neutron fluence of 10^{14} cm^{-2} is the same as that produced by 10^{16} electrons cm^{-2} with energy above 3 MeV. Tests on the optical transmission of Hamamatsu radiation-hard glass following ^{60}Co irradiation are in progress at Brunel University.

Several measurements have been made of the sensitivity of phototubes to high-energy radiation. RIE have investigated the influence of γ-radiation, neutrons and protons on the photocathode sensitivity of a number of commercial photomultipliers. No damage was observed with a 1 Mrad gamma ray dose or following an exposure to 10^{14} neutrons cm^{-2}. The radiation hardness of a FEU-115 photomultiplier with a faceplate of C96-1 glass, produced by the Moscow Factory MELZ, is reported in [4.16]. No changes in faceplate transparency were observed with a 35 Mrad ^{60}Co gamma irradiation, and in output signal amplitude up to 15 Mrad.

At a rapidity of 3.0 the background in the ECAL is estimated to correspond to an energy deposition per crystal of about 2×10^7 GeV/s [4.17]. This is expected to lead to a photocurrent in excess of 10nA, sufficient to reduce the gain and resolution of a tube. Measurements by BNPI (Novosibirsk, Russia) [4.17] showed that the production of a total charge of 0.1 C, approximately one year's operation at 10 nA, caused a 10% reduction in the gain. Additional measurements of long-term gain stability will be performed on a number of prototypes during the coming year.

The sensitivity of photomultiplier tubes to relativistic protons and gammas has been measured in [4.18]. Photomultipliers respond to relativistic charged particles via the production of Cerenkov radiation in the faceplate. The response to gamma rays with energies above about 1 MeV is due to the production of fast electrons or positrons in the faceplate by Compton scattering or pair production and the subsequent emission of Cerenkov radiation by the charged leptons. For charged particles, the photomultiplier response is proportional to the faceplate thickness. For gammas, to the thickness squared. A relativistic charged particle traversing a 1 mm-thick borosilicate glass faceplate typically produces 6 photoelectrons. More would be expected from a quartz faceplate of the same thickness, because of the greater transmission of quartz at short wavelengths and the λ^{-2} behaviour of the Cerenkov spectrum. A 1 MeV gamma ray passing through a 1 mm-thick borosilicate glass faceplate produces only 0.25 photoelectrons, on average. Gavrilov et al, [4.19], calculated that, even in the background fluxes expected in the very forward calorimeter, the contribution to the signal in a 2" diameter photomultiplier would be 0.04 photoelectrons per bunch crossing due to relativistic charged particles and 0.01 photoelectrons per bunch crossing for gammas with energies above 1 MeV.

4.2.4 Further tests

A substantial programme of vacuum phototriode and phototetrode testing is in progress both in Russia and the UK. The PNPI group is planning to test a 3×3 array of full-size $PbWO_4$ crystals with prototype phototriodes in a CERN test beam during October/November 1997. Sample phototriodes from RIE, Hamamatsu and Electron Tubes will be tested at RAL using pulsed LEDs in quasi-axial magnetic fields up to 4 T on a similar timescale.

References

[4.13] R. M. Brown et al, IEEE Trans NS32 (1985) 736.

[4.14] M. Bonesini et al Nucl. Instr. Meths. A387 (1997) 60.

[4.15] S. Ahmad et al, Nucl. Instr. Meths. A387 (1997) 43.

[4.16] S. A. Belianchenko et al, IHEP-Preprint 96-10, Protvino, 1996.

[4.17] I. Azhgiray et al, Proc. 15th Conf. Charged Particles and Accelerators, Protvino, 1996; http://wwwinfo.cern.ch/~talanov

[4.18] P. M. Bes'chastnov et al, Nucl. Instr. Meths. A342 (1994) 477.

[4.19] V. Gavrilov et al, CMS Technical Note No. CMS TN/95-146, November 1995.