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CMS NOTE 1998/080

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

9 December 1998

Fine–Mesh Photodetectors for CMS Endcap Electromagnetic Calorimeter

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RDMS/UK Collaboration

Abstract

The behaviour of fine-mesh vacuum phototetrodes and phototriodes (VPTs) in an axial magnetic field of $(0 \div 4)$T has been investigated. The measured VPT parameters are: fine-mesh cell dimensions, the photocathode sensitivity and its homogenity, the gain in zero and 4T magnetic field at tilt angles corresponding to the rapidity range of CMS ECAL Endcap $1.479 \div 3.0$ and excess noise factor. Measurements have been performed on 21 and 30 mm diameter photodetectors with different fine-mesh structures: 30, 60 and 100 lines per mm under different types of photocathode illumination by green LED. Phototriodes with 30 or 60 lines per mm and an external diameter of 21 mm are found to be the best candidates for the CMS environment with the initial size of PWO crystals proposed to be used in the Endcap, by comparison with phototetrodes. They provide a gain of the order of $6 \div 8$ in 4T magnetic field and an excess noise factor of 2 under full photocathode illumination.

To be submitted to Nucl. Instr. and Meth.

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1 Introduction

The photodetectors for the ECAL Endcaps of the CMS-Detector covering the rapidity range 1.479<$|\eta|$<3.0 are required to operate in a uniform 4T axial magnetic field, should survive radiation exposures up to 5 kGy/year and must offer an adequate signal-to-noise ratio with the low light yield of $PbWO_4$ crystals . The avalanche photodiodes (APD) proposed for use in the barrel ECAL are insensitive to magnetic field, provide gain in the region of 50 and offer satisfactory signal-to-noise performance. However, they are insufficiently radiation-hard for use over the whole rapidity range covered by the Endcap ECAL.
Fine-mesh photomultipliers with low gain, such as phototriodes or phototetrodes, are candidate photodetectors for the ECAL Endcaps. Vacuum phototriodes with an external diameter of 21 mm have about the same order total efficiency (quantum efficiency $\times$ sensitive photocathode area) for the detection of $PbWO_4$ light as 50 mm^2 APD's, and are much more radiation hard.

Hamamatsu 25 mm vacuum phototriodes have been successfully used in the DELPHI STIC experiment [1] and had an acceptable gain $(7-9)$ in 4T magnetic field [2]. Hamamatsu 77 mm phototetrodes being implemented for the NOMAD-CERN experiment [3] showed good long term stability in 0.4T transverse field. In moderate magnetic fields - up to (1.5 - 2.0)T - phototetrodes with external diameters of 21, 30 mm (FEU-188, FEU-187 RIE) and 25 mm (Hamamatsu Photonics) have a gain of about 15, which is weakly dependent on photocathode size, and is approximately twice that of a triode, as shown in Fig.1a. In the absence of magnetic field, phototetrodes provide a gain about 30 and phototriodes about 12. But in a stronger magnetic field, (Fig.1b) the phototetrode's gain degrades more than that of the phototriode and, at B =4T, their gains are approximately equal.

In the rapidity range of the CMS ECAL Endcaps tilt angles $\Theta = (6 \div 26)^{\circ}$, 21 mm phototriodes (RIE) provide a gain at B =4T of the order of $6 \div 8$. Triodes are expected to be cheaper than tetrodes. As result of these considerations the CMS ECAL Endcaps will employ vacuum fine-mesh phototriodes.

For maximum light collection the VPT diameter should be as large as possible, subject to constraints imposed by the cross-section of the crystal and the need to allocate space for mechanical support. Initially it was supposed to use VPT's with an external diameter of 21 mm, but now $PbWO_4$ crystals with end dimensions (30 $\times$ 30)mm^2 have been chosen the VPT diameter has been established to be 25mm. We present, mainly, parameters of 21 mm RIE phototriodes and their behaviour in magnetic fields. Results of 25 mm triode R&D will be given in the next publication.

2 Device parameters

2.1 Design and photocathode parameters.

In recent years a new generation of photomultipliers with fine-mesh dynodes (FMPMT) having excellent time resolution (50 ps) and able to operate in axial magnetic fields up to 1T have been produced. Such multistage $(12 \div 19)$ PMTs are manufactured by Hamamatsu Photonics. Between 1995 and 1996, the Russian electronics firms, RIE (St. Petersburg) and MELZ (Moscow) designed and constructed experimental batches of 30 mm 15 stage FMPMT - FEU-527 [4,5], which are in many respects similar to Hamamatsu R3432-01 and R5505 tubes.

During 1996 - 97, RIE, in the collaboration with PNPI have been performed research on the design and construction of fine-mesh phototubes of low gain: 30mm tetrode FEU-187, 21 mm tetrode FEU-188 and 21 mm triode FEU-189, with meshes of 30, 60, and 100 lines per mm. Electron Tubes (ET UK) in collaboration with Brunel University has performed R&D on 22 mm phototriodes with mesh dimensions of 8 and 16 l/mm and manufactured experimental samples of VPT [6].
Initially, 21mm tetrodes were considered as possible candidates for photoreadout of the CMS ECAL Endcap and were tested on an electron beam at CERN, together with normal vacuum phototriodes. They showed a good linearity in the e^- energy range $(10 \div 45)$ GeV. As indicated above at 4T phototriodes seem preferable. Nevertheless, for operation in fields $(1 \div 2)$ T the tetrode FEU-188 is a good photodetector.

Figure 2 shows a schematic view of a phototriode FEU-189 and the connector of power supplies for testing VPTs. In ECAL Endcap operation the photocathode will be grounded, the mesh anode will be operated at $(800 \div 1000)$V and solid dynode at about $(600 \div 800)$V. In our case for VPT testing, we grounded the mesh anode, $V_{ca} = -(800 \div 1000)$V and $V_{ad} = -(100 \div 300)$V. A planar, bialkali, semitransparent photocathode is deposited on the inner surface of a normal faceplate glass, whose transparency is more than 50% at λ=350 nm. For long-term operation in a high radiation environment the faceplate is proposed to be made from radiation-resistant glass C1-96.

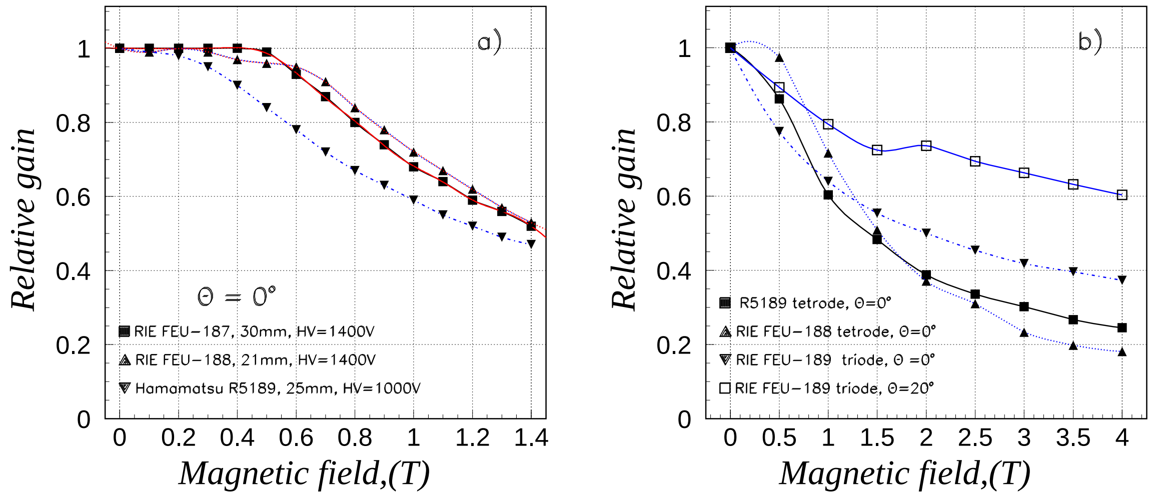


Fig.1 Relative gain of different types of fine mesh detectors as a function of magnetic field. Illumination of the central part of photocathode (8 mm diameter).

The photocathode is characterized by a low dark current $(\leq)5$ nA and a quantum efficiency QE, with maximum values $(18 \div 28)\%$ in the spectral region $(350 \div 400)$ nm as shown in Fig.3. The emission spectra of $PbWO_4$ dopped by La and Nb are also shown. Such doped $PbWO_4$ crystals are expexted to be used in the CMS ECAL. The distribution of the total cathode sensitivity (μA/lm) for the experimental batch of FEU-189 is shown in Fig.4. There is an approximate linear correlation between the total cathode sensitivity and the radiant cathode sensitivity at the peak of $PbWO_4$ emission spectra ($\lambda = 430 \div 450$) nm, defined QE of the photodetectors.

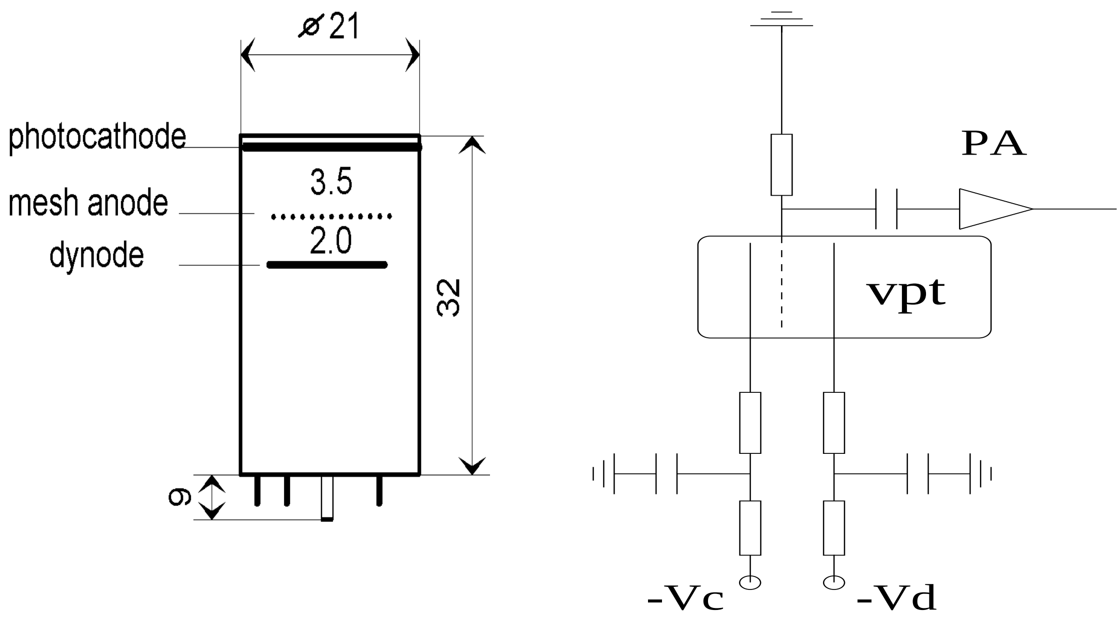
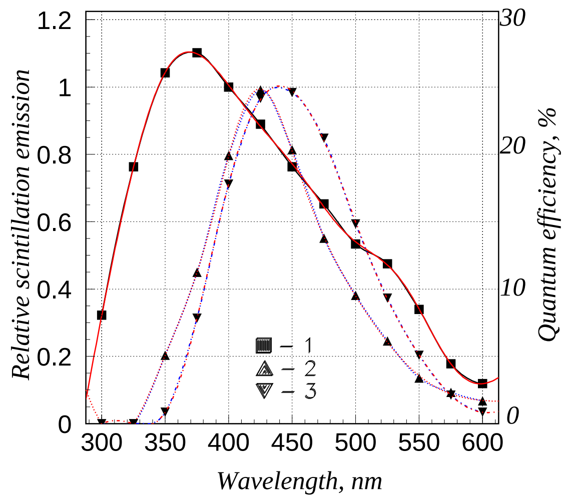


Fig.2 Schematic view of FEU-189 VPT and power supply connections employed for testing VPTs.



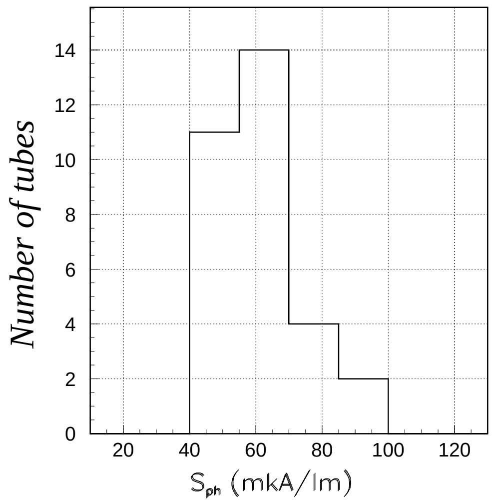
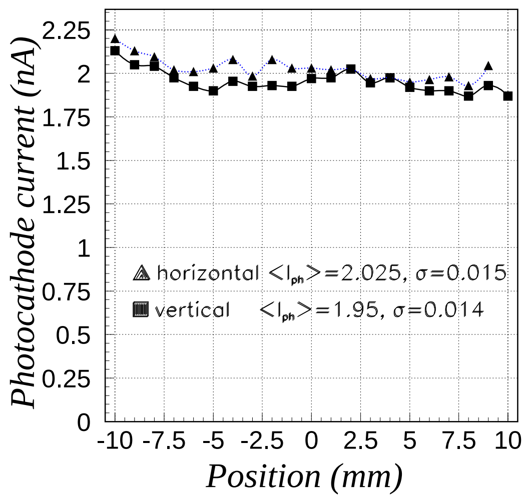


Fig.3 Quantum efficiency of FEU-189 photocathode (1) and emission spectra of $PbWO_4$ crystals doped by La (2) and Nb (3).

Fig.4 Distribution of total photocathode sensitivity for experimental samples of FEU-189, $< S_{ph} >= 61\mu A/lm$.

The range of $S^t_{pc} = (50 \div 110)$ μA/lm for the VPT samples corresponds to $S^r_{pc} = (40 \div 70)$ mA/W. The differential photocathode response was measured in two perpendicular directions steps of 1 mm using a collimated light source. The dependence of photocathode current at different points along the X and Y axes for a 30 mm tetrode FEU-187 is shown in Fig.5. The distribution of the gain for the FEU-189 triode samples is presented in Fig.6.



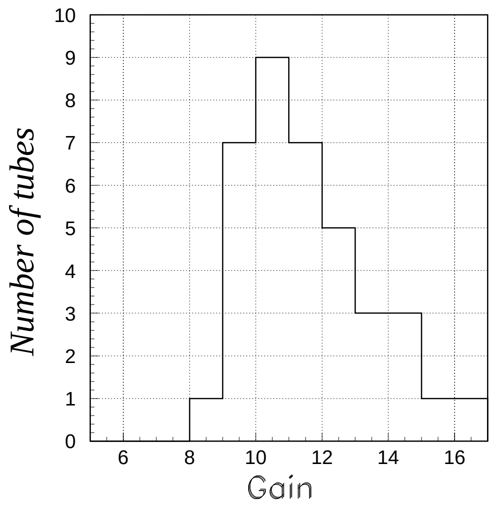


Fig.5 Photocathode current as a function of illuminated point position on two axes: horizontal and vertical for FEU-187. The centre of photocathode is at the origin.

Fig.6 Gain distribution of the triode samples, $< G >= 11.6$.

2.2 Gain in zero magnetic field.

The gain of phototetrodes, as shown in [3] and according to our measurements, depends linearly on the applied voltage and has a maximum when the HV between cathode-first dynode is equal to $0.5 \div 0.6$ of the total HV. The dependence of phototriode gain on the applied voltage is more complicated (see Fig.7 and 8) and [7,8]. A large fraction of the photoelectrons liberated from the photocathode passes through the anode mesh and impacts on the solid dynode, where secondary electrons are produced. With a high-gain dynode the secondary emission factor can be as high as 20. The secondary electrons are attracted to the anode mesh where a substantial fraction is captured forming the anode signal. Because flight times in cathode-anode-dynode gaps are of the order of $(0.2 \div 0.5)$ns the signal time spread in the whole amplification process is less than 1ns. The gain of the triode depends on the design parameters of the VPT: the applied voltages and the transparency of the mesh cell. Fine-meshes with 30, 60, 80 and 100 lines per mm are usually used in such photodetectors (Hamamatsu, RIE) with a mesh optical transparency in the range 30–70% . The transparency of normal phototriodes with a mesh spacing of 0.25 mm (4 l/mm) [9] can be as large as 95% but such detectors have acceptable gain only in magnetic fields up to 2-2.5T.

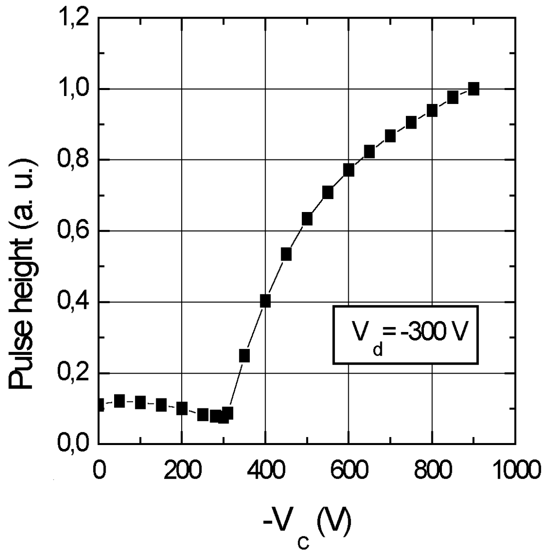


Fig.7 The variation of the gain with cathode voltage of VPT FEU-189.

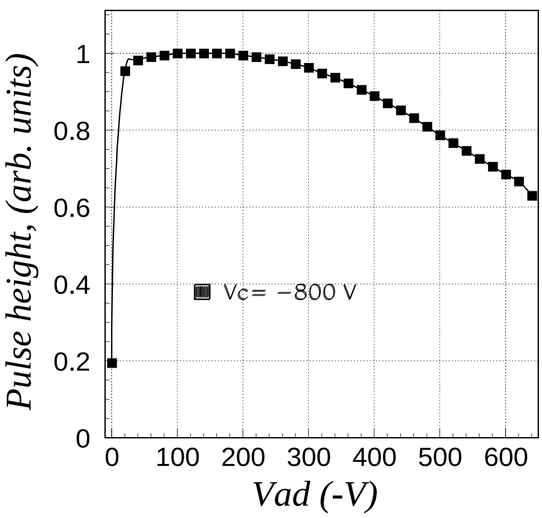


Fig.8 Gain of VPT FEU-189 as a function of anode-dynode voltage.

2.3 Gain in magnetic field.

The principal effect of operating a vacuum device in a strong magnetic field is that the electrons are constrained to move in tight spirals around the field lines. At the 4 T the spiral radii are of the order of microns. In an axial field, electrons from the periphery of the photocathode, which is larger than the useful area of the dynode, are lost. But as it is seen from Figures 1 and 9 the gain at B =1.4 T and 4 T is larger when the inclination of the tube to the magnetic field direction, Θ, is $20°$ or $30°$. This can be partially explained by an increase of the fine-mesh surface for penetrating electrons at$\Theta > 0$. Also if the field is not axial, some electrons spiralling along the field lines will be swept to the sides of the tube and lost. The gain is strongly dependent on the photocathode illumination. This is an important consideration during testing, as fewer electrons are lost if only the center of the photocathode is illuminated.

The behaviour of the tube is also dependent on the mesh size of the electrodes. A fine mesh stands a better chance of intercepting tightly spiralling electrons, and the probability of collision is also enhanced if the field lines are at an angle to the plane of the mesh. On the other hand, in the phototriode, photoelectrons are required to penetrate the mesh anode in order to reach the dynode. The use of a less transparent mesh will result in the photoelectrons failing to reach the dynode with a consequent reduction in gain and increase in excess noise factor.

We investigated the “magnetic hardness” - the ratio of the gain in an axial magnetic field to the gain at zero field for a number of VPT's (FEU-189) with different sizes of mesh (30, 60 and 100 l/mm). Phototubes were illuminated with a green LED. The initial experiments were performed in "warm" magnet with B_{max}=1.4 T, the final ones in a super conducting solenoid (PNPI). The results are shown in Fig.9,10. The data of Fig.9 demonstrate that fine mesh (100 l/mm) increases G/G_0 for zero tilt angle at B =1.4 T while measurements at B =4 T don't provide any evidence for such dependence (see Fig.10). However the data of Fig.9 and Fig.10 were obtained under different conditions of photocathode illumination.

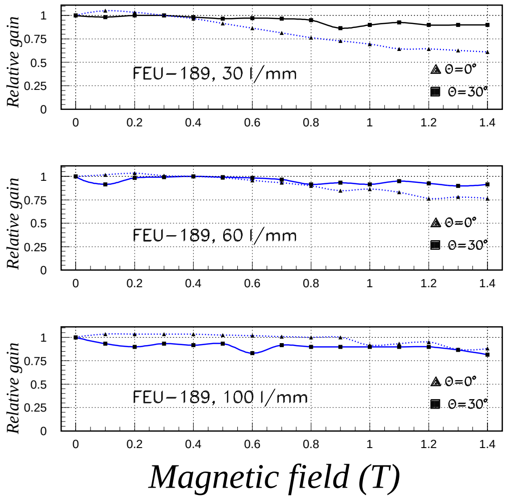


Fig.9 Relative gain as a function of magnetic field at $\Theta = 0^{\circ},\ 30^{\circ}$ for FEU-189 with different sizes of mesh. Illumination of central part of photocathode; spot 8 mm in diameter.

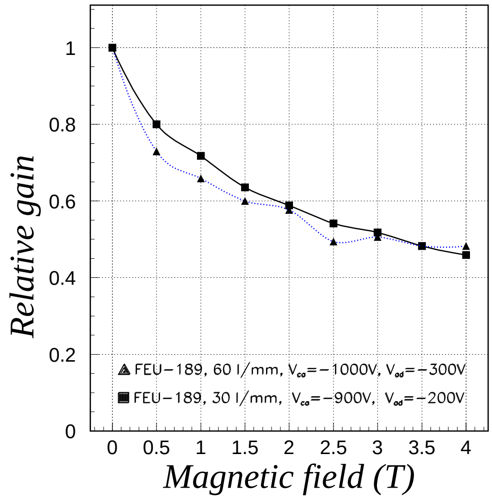


Fig.10 Relative gain as a function of magnetic field at $\Theta = 0^{\circ}$ for different phototriodes. Full photocathode illumination.

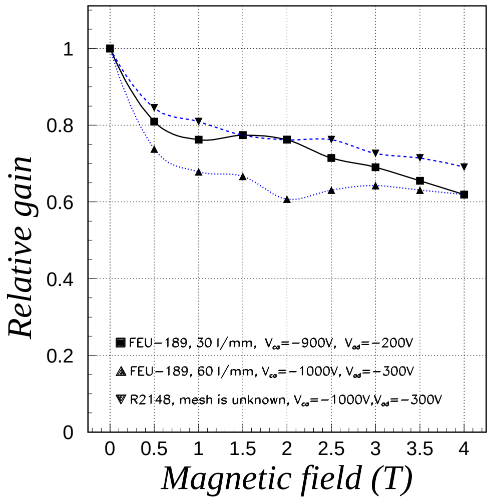


Fig.11 Relative gain as a function of magnetic field at $\Theta = 20^{\circ}$ for different phototriodes.

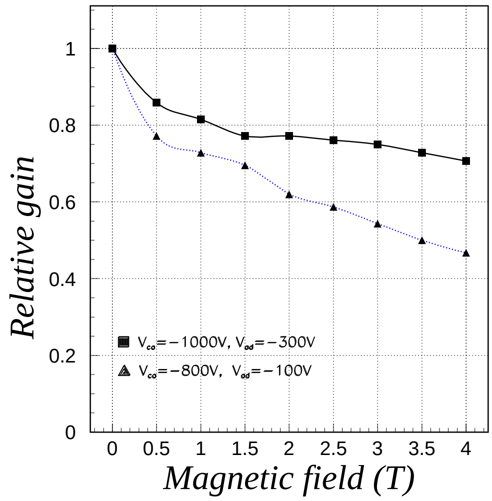
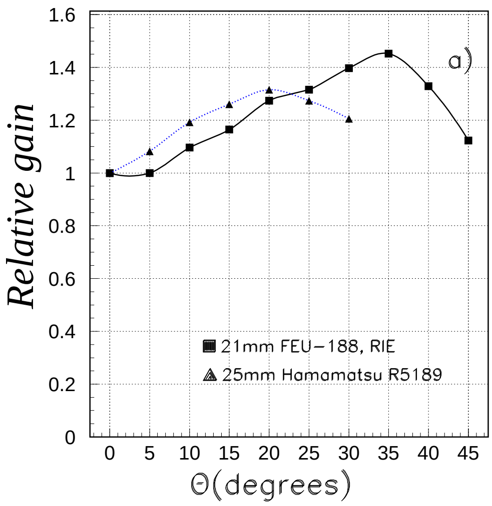


Fig.12 Relative gain as a function of magnetic field for Hamamatsu triode R2148 at different cathode and dynode voltages ($\Theta = 20^{\circ}$).

Figure 11 shows the magnetic hardness of different types of VPT in a magnetic field up to 4T at $\Theta = 20°$. The final value of G/G_0 at B =4T is the same for RIE FEU-189 with different mesh sizes (30 and 60 l/mm), but the existence of a plateau in the magnetic field dependence of G/G_0 from 2 up to 4T is a some evidence in favour of 60 l/mm phototriodes for use in the ECAL Endcap.

A significant advantage of using a VPT is that the gain is weakly dependent on the electrode bias voltages; typically $(dM/dV)/M < 0.1\%$/V in zero magnetic field (see Fig.7 and 8). Bias currents to the electrodes are also very low, so that if anode and dynode bias voltages are provided from separate supplies, power dissipation in the vicinity of the device due to the flow of bias current can be less than 100 μW. But in a magnetic field as shown in Fig.12 for a Hamamatsu triode the dependence on applied voltage is greater than at B =0. A change of 200 V in the cathode and dynode HV increases the gain at 4T by 35%. The dependence of VPT gain on $V_a - V_d$ in small magnetic fields, ($B = 0.4$T), is less than at 4T. Increasing the anode-dynode voltage by 200 V, (from -800/-100 to -1000/-300 see Fig.12), for a Hamamatsu VPT increases the gain by 9%. For an ET VPT such a change of HV gives a gain increase of 18%. Thus a very important requirement at the VPT is the possibility of operating with an applied voltage as high as possible, in order to have a gain in a 4T magnetic field at the level of $8 \div 10$ in the Endcap rapidity range with tilt angles $6° \div 26°$.



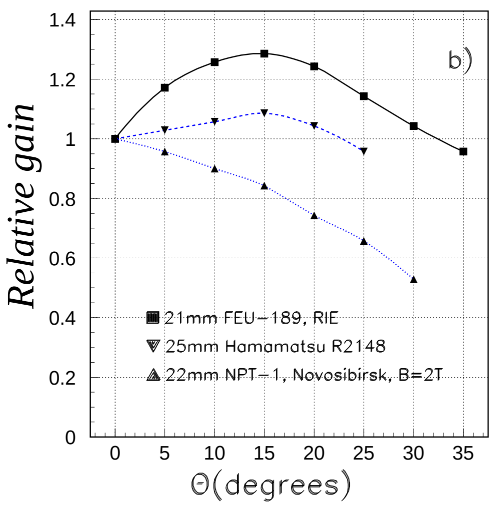


Fig.13 Relative gain as a function of tilt angle for different types of photodetectors at B =1.4T, a) - phototetrodes, b) - phototriodes.

Fig.13 shows the angular dependence of the gain of phototetrodes and phototriodes behaior in a 1.4T magnetic field. Tetrodes and triodes with fine-mesh electrodes show normal behavior in the magnetic field up to tilt angles of $35° \div 40°$. Vacuum triodes (NPT - 1) have half the gain in a 2T magnetic field at $\Theta = 30°$ compared with fine-mesh ones. Fig.14 shows the FEU-189 magnetic hardness of two types of device with 30 and 60 l/mm meshes in a 4T field. In the region $5° \div 30°$ both types of VPT demonstrate very weak dependevce of G/G_0 on the size of the mesh cell. A Hamamatsu triode R2148 shows a very weak dependence of the gain on the tilt angle measured at PNPI (Fig.13) at 1.4T and at RAL [6] at 4T (Fig.14). Another criterion for the final choice of VPT mesh may be the noise performance of phototriodes.

2.4 Excess noise factor.

Vacuum devices have a low output capacitance, with the result that the input capacitance of the preamplifier is dominated by the capacitance of the connecting leads. The intrinsic noise of vacuum phototriodes is low and initial tests indicate that the system noise will be dominated by the input capacitance and the preamplifier electronics noise. A system noise level of approximately 3000 e^- r.m.s. is anticipated. In phototriodes as in other detectors multiplication is a random process leading to additional fluctuations of the collected charge. These fluctuations are characterized by the excess noise factor F, with the r.m.s. broadening of a signal from N photoelectrons given by $\sqrt{F/N}$. In phototriodes the value of F is mainly defined by the grid transmission factor ε. For a mesh cell of 30 l/mm the optical transmission is equal to $70 \div 75\%$, that results in a calculated value of F, to a rough approximation, of 1.5–2.0.

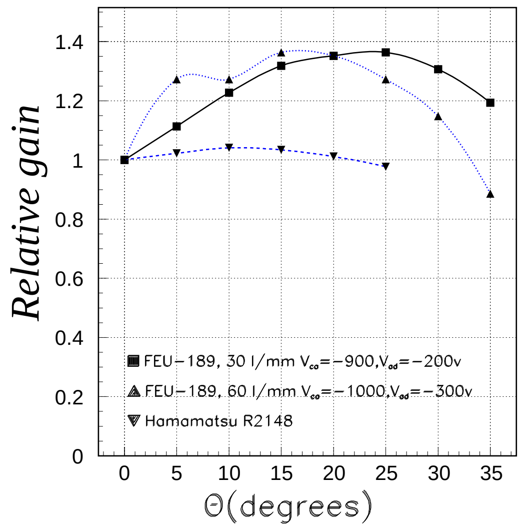
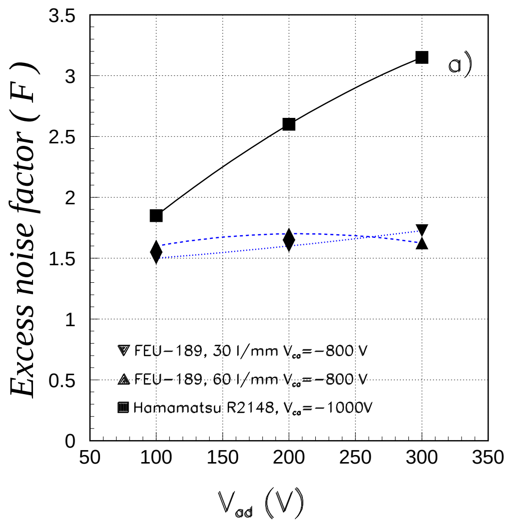
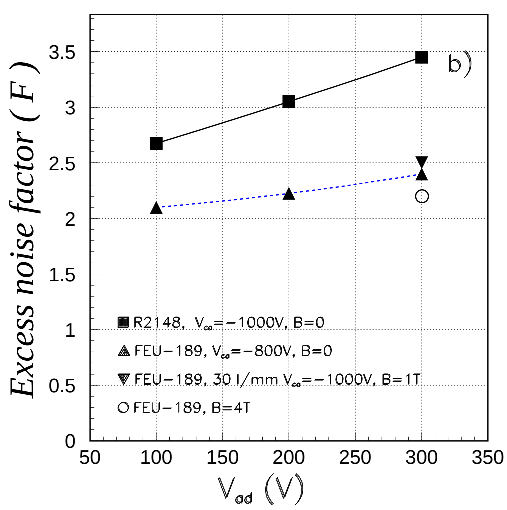


Fig.14 Tilt angle dependences of the gain for a FEU-189 VPT with different mesh dimensions and a Hamamatsu R2148 triode at B =4T.



Illumination of the central part of photocathode, spot diameter = 8 mm.



Illumination of full photocathode area.

Fig.15 Excess noise factor as a function of anode-dynode voltage for different phototriodes and conditions of photocathode illumination.

We measured F values for a RIE 21 mm VPT with different sizes of mesh under illumination of the central part of the photocathode and full area illumination by the green LED in zero magnetic field and in fields up to 4T.
The value of F is defined as $(\sigma_{anode}/S)^2 \times N$.
Where $\sigma^2_{anode} = \sigma^2_{tot} - \sigma^2_{el}$, S - anode signal, N - the number photoelectrons produced by the photocathode. σ, S and N are measured in e^-. A spectrometer with a low noise preamplifier was used for the measurements. The calibration of the channel consisting of preamplifier, amplifier and ADC was performed with signals from a pure Ge detector irradiated by γ -rays from $^{137}Cs, ^{60}Co, ^{241}Am$ and a pulse generator. A noise of electronics is measured as $700e^-(\sigma)$. Results of measurements of F in zero, 1T and 4T magnetic fields at different values of anode - dynode voltage for RIE 21 mm and Hamamatsu 25 mm VPTs are shown in Fig.15. RIE phototriodes are characterized by a weak dependence of F upon V_{ad} while a stronger correlation between F and V_{ad} is observed for the Hamamatsu tube. Increasing the illuminated photocathode area increases F in a zero field. The measurements of F in a 1T and 4T magnetic fields show weak sensitivity to B for 30 l/mm RIE triodes. On the other hand excess noise factors in zero magnetic field are the same for tubes with 30 and 60 l/mm (Fig.15). Typical parameters of a RIE VPT are given in Table 1.

Table 1. Parameters of the RIE FEU-189 VPT.

Parameter	**Value**
External diameter	21 mm
Photocathode useful diameter	15 mm
Overall length	41 mm
Operating bias voltages: V_a, V_d ($V_c = 0V$)	1000 V, 800 V
Dark current	$1 \div 10$nA
$(dM/dV)/M$	<0.1%/V
$(dM/dT)/M$	<0.1%/C
Quantum efficiency at 430 nm	>15%
Range of spectral response	$300 \div 620$ nm
Effective gain (B =0 T)	12
Effective gain ($B = 4T, \Theta = 0°$)	6
Effective gain ($B = 4T, \Theta = 20°$)	8
Anode pulse rise time	1.5 ns
Excess noise factor, F at B =0	$2.0 \div 2.5$
Excess noise factor, F $B = 1\div$ 4T, $\Theta = 20°$	$2.2 \div 2.6$

The Brunel group [7] studied an ET VPT (16 l/mm) in a magnetic field up to 0.4T, finding F to be $1.5 \div 2.0$ in this region. The main conclusion from the above data is that the excess noise factor for RIE and ET $21 \div 22$ mm phototriodes lies in the interval $2.0 \div 2.5$ in zero magnetic field and in fields up to 4T, weakly dependent on the size of mesh. The final choice of the mesh for 25 mm VPT for the CMS ECAL Endcap requires additional measurements and simulations of the VPT gain and F - factor in a 4T magnetic field.

A matrix of 3×3 experimental samples of 21 mm RIE and ET VPTs coupled with $PbWO_4$ crystals were tested in at (50–180)GeV electron beam in zero and 3 T magnetic fields at CERN in summer 1998. The energy resolution and linearity approached the values required for the ECAL Endcaps.

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