STATE RESEARCH CENTER OF RUSSIA
INSTITUTE FOR HIGH ENERGY PHYSICS

IHEP 2004–23

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PHOTOTRIODES AND PHOTOTETRODES WITH HIGH GAIN

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Protvino 2004

UDK 539.1.074 M-24

Abstract

Belyanchenko S.A., Brekhovskikh V.V., Dyatchenko V.A. et al. Phototriodes and Phototetrodes with High Gain: IHEP Preprint 2004–23. – Protvino, 2004. – p. 8, figs. 9, tables 2, refs.: 6.

The new results on the design and characteristics of phototriodes with a gain of 30–50 and phototetodes with a gain up to 200 are described. These photoreceivers were designed and produced at IHEP and MELZ in the last four years. MELZ has started to produce such phototriodes with radiation hardened Ce-doped photocathode window. The possibilities of using these results for photomultipliers designing which can operate in magnetic fields more than 4 T, multichannel photomultipliers and particle detectors with high time resolution are discussed.

Аннотация

Белянченко С.А., Бреховских В.В., Дятченко В.А. и др. Фототриоды и фототетроды с высоким усилением: Препринт ИФВЭ 2004–23. – Протвино, 2004. – 8 с., 9 рис., 2 табл., библиогр.: 6.

Описаны новые результаты по характеристикам фототриодов с усилением 30–50 и фототетродов с усилением до 200. Эти фотоприёмники были разработаны и изготовлены в ИФВЭ и на МЭЛЗе в течение последних четырёх лет. На МЭЛЗе освоено производство фототриодов с высоким усилением и радиационно стойким окном фотокатода. Обсуждаются возможности использования результатов разработок для создания фотоумножителей, работающих в магнитных полях более 4 Т, многоканальных фотоумножителей и детекторов частиц с высоким временным разрешением.

Introduction

Energy resolution of the CMS Forward ECAL along with other factors is defined by the phototriodes gain, which determines the equivalent noise value [1].

The minimum desirable value of required gain is around that of 10 in 4T axial magnetic field. At the same time the mean gain value of tested phototriodes with bialkali dynode of a reflective type and a fine-mesh anode does not exceed the value of 12–16 [1, 2] and decreases by a factor of 2 in the magnetic field of 4 T.

In the frames of the CERN-INTAS project 99-0424*, IHEP in collaboration with MELZ, has designed and successfully tested the first samples of phototriodes with a gain of 30 or more. MELZ is about to reach the production stage of the fine-mesh phototriodes with gains of 30-50, and radiation-resistant C1-96 glass faceplates.

A design of the phototetrodes with shoot through and reflective types dynodes and a gain up to 200 was a next step in the magnetic field hard photoreceiver development.

The original data on the secondary emission gain of bialkali K_2CsSb and multialkali Na_2KCsSb dynodes were obtained by A.H. Sommer [3]. For the electron energy of 800 eV, these gain values were around 25 and 30 respectively. Therefore not all possibilities in the tested phototriodes [1, 2] with bialkali dynodes were realized. Our results for the gain differ from typical manufacturer device characteristics (e.g. Hamamatsu, Philips, Research Institute Electron) and are as three times higher.

1. Main characteristics of high gain phototriodes

Sketch of IHEP and MELZ phototriodes construction, scheme of characteristics measurements and dependencies of phototriodes gain versus different parameters are shown in **Fig. 1–3**.

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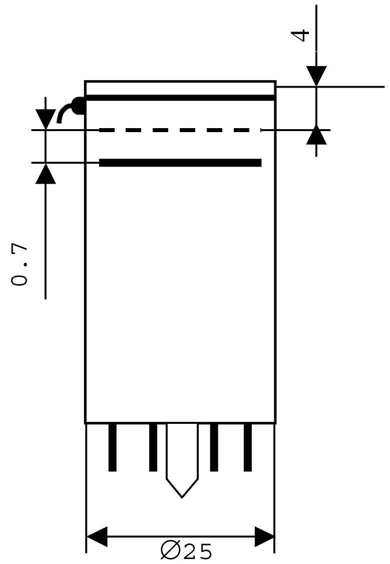
*Design and Test Suitable Vacuum Phototriodes for the Forward Region of the CMS Electromagnetic Calorimeters.



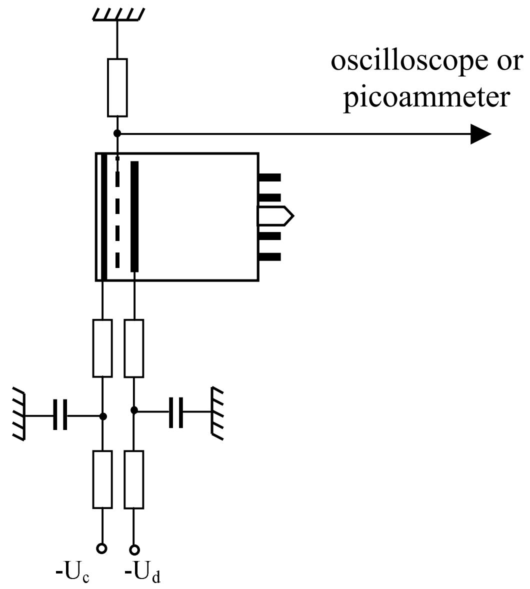


Fig. 1. Sketch of VPT construction.

Fig. 2. Scheme of characteristics measurements.

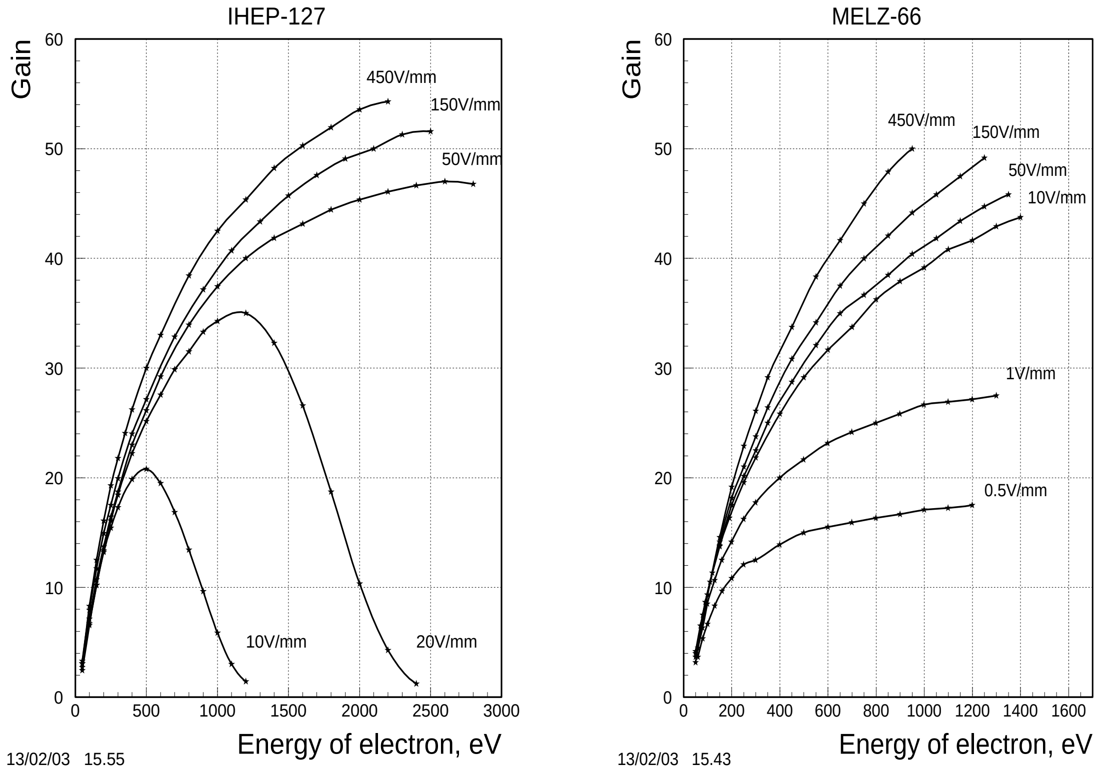


Fig. 3. Dependencies of phototriodes gain on photoelectron energy and electric fields in the dynode–anode gap for IHEP-made and MELZ-made phototriodes.

The main characteristics of designed phototriodes with radiation-resistant glass faceplates are presented in **Table 1** in a comparison with Hamamatsu R2148 vacuum phototriode.

Таблица 1. Main characteristics of MELZ phototriodes

№, Manufacturer	$S_{ph.cath}$ 410 nm mA/W	Gain	HV_{nom} (kV)	HV_{max} (kV)	Anode signal ampl. LED, 430 nm	Photo-cathode signal ampl. LED, 430 nm	Type of mesh
Hamamatsu	80	9	1	1	1	1	
48, MELZ	54	47	1.85	2.4	2.34	0.3	Cu, 60 l/mm
50, MELZ	50	39	1.85	2.4	2.2	0.34	Cu, 60 l/mm
54, MELZ	51	46	1.85	2.05	3.1	0.42	Cu, 60 l/mm
57, MELZ	62	20	1.85	2.4	2	0.64	Cu, 100 l/mm
59, MELZ	47	44	1.85	2.4	2.6	0.38	Cu, 100 l/mm
61, MELZ	62	35	1.85	2.85	2.65	0.47	Si, 100 l/mm
63, MELZ	51	35	1.85	2.45	2.5	0.44	Cu, 100 l/mm
64, MELZ	44	37	1.85	2.45	2.2	0.36	Si, 100 l/mm
65, MELZ	40	36	1.85	2.4	1.8	0.3	Si, 100 l/mm
66, MELZ	49	35	1.85	2.05	2.2	0.38	Cu, 60 l/mm
69, MELZ	52	41	1.85	2.45	2.5	0.38	Cu, 60 l/mm
71, MELZ	53	52	1.85	2.45	2.24	0.24	Cu, 60 l/mm
74, MELZ	40	49	1.85	1.9	1.7	0.45	Cu, 60 l/mm
Mean, MELZ	50.4	40	1.85	2.4	2.3	0.39	

As we see from Table 1, the gain of MELZ phototriodes is a few times more than R2148, but their mean blue photocathode sensitivity is at least two times less. Therefore there is an opportunity to increase the output signal from MELZ phototriodes.

2. Possible nature of process of high gain

The known results of the secondary emission coefficient (δ) measurements for K_2CsSb, Na_2KCsSb, Cs_3Sb, GaP and Cu-BeO-Cs dynodes are shown in **Fig. 4** [4, 5].

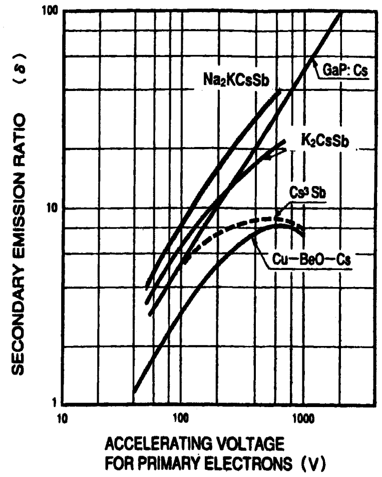


Fig. 4. Dependencies of a secondary emission coefficient of different effective dynode types on electron energy.

As one can see from Fig. 4, there is not any significant saturation of δ versus the accelerating voltage for bialkali and multialcali dynode cases. Besides that, it is not known under what values of electric field, “collecting” secondary electrons, these measurements have been carried out. At the same time the results presented on Fig. 3 show that a dependence of a gain (δ) from a collecting field can be sufficiently strong.

It seems that the explanation of the high emission coefficient value of these dynodes, being due only to the effective Negative Electron Affinity (NEA) [4] similar to that of GaP(Cs), is not sufficient for the case of the K_2CsSb dynode. The dependencies in Fig. 3 show that the gain of these phototriodes increases with the stepping up of electric field in the dynode–anode gap, but a gain saturation and then a gain decrease takes place for small values of this electric field only. This may indicate that electric field penetrates into the dynode material to the depth of at least the photoelectron range in the K_2CsSb dynode. This may be true because K_2CsSb is the semiconductor with a very high resistivity of a few kOhm/cm and the number of carriers can be insufficient to compensate the outside electric field.

The following qualitative model seems to be more real:

1. K_2CsSb layer has a relatively small value of the surface potential barrier.
2. Electric field inside K_2CsSb dynode “warms up” and transports secondary electrons to the surface, but does not lower the value of a potential barrier on the surface of the dynode as there is the very weak dependence of a gain from an electric field in the region of the small value of photoelectron energy (Fig. 3).

3. Phototetrodes with shoot through thin film dynodes

In the frames of the specified INTAS project the new type of a photoreceivers – the phototetrodes with shoot through thin film dynode have also been designed. Sketches of the phototetrode construction and scheme of its characteristics measurements are shown in **Fig. 5** and **6** respectively.

The dependencies of gain of shoot through dynodes d1, reflective dynodes d2 and phototetrodes in whole on several parameters are presented in **Fig. 7–9**.

Maximum gain of the shoot through dynode was achieved for a minimum thickness of the active film with sufficient mechanical stability. This thickness is around 50 nm at a surface density of (0.1±0.01) mg/cm^2. However there is a real technical opportunity of the further reduction of thickness of an active film.

At the same time for example a length of 2 kV electron range is $(4.5\pm3)\cdot10^{-3}$ mg/cm^2 i.e. in 22 times less. In a case of 0.5 keV electron energy this ratio (22) will be more on two orders of value, but secondary emission takes place yet. This means that:

1. All secondary electrons are thermolized.
2. Diffusion length of secondary electrons inside the active film should be comparable with the film thickness.

As it is seen from Fig. 7, the gain of shoot through dynodes depends relatively weakly on the electric field in the shoot through dynode–anode gap. It seems that the electric field does not penetrate in the volume of the dynode and can not “warm up” and transport secondary electrons to the output surface of the dynode.

It is possible to explain these facts with the assumption that the surface of the designed active film of the shoot through dynode has Negative Electron Affinity similar to that of GaP(Cs).

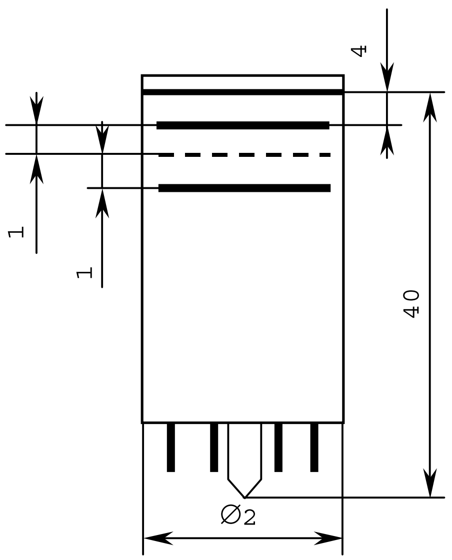


Fig. 5. Sketch of the phototetrode construction.

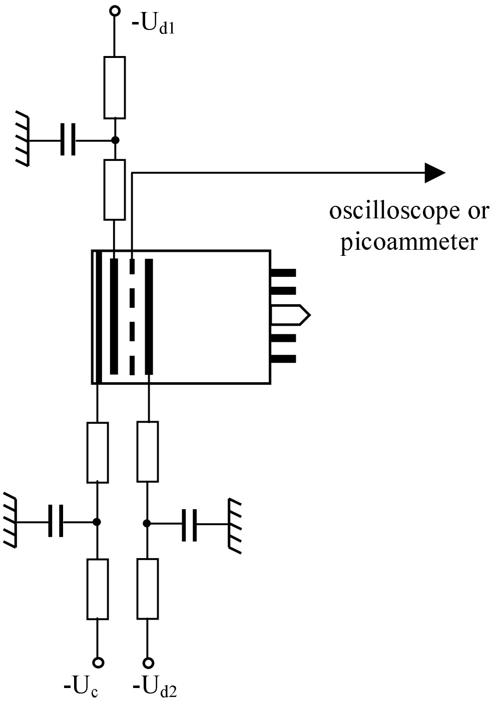


Fig. 6. Scheme of characteristics measurements.

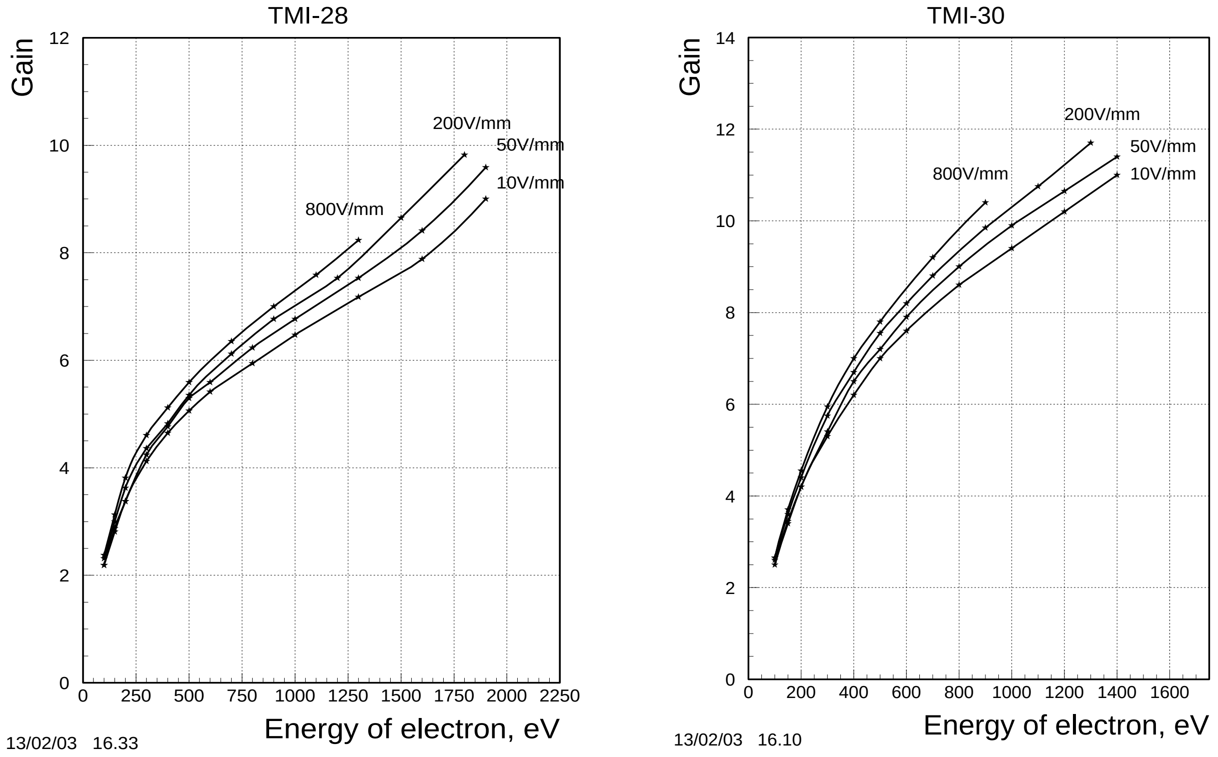


Fig. 7. Dependencies of a shoot through dynode gain on photoelectron energy and an electric field between this dynode and anode for TMI-28 (left) and TMI-30 (right).

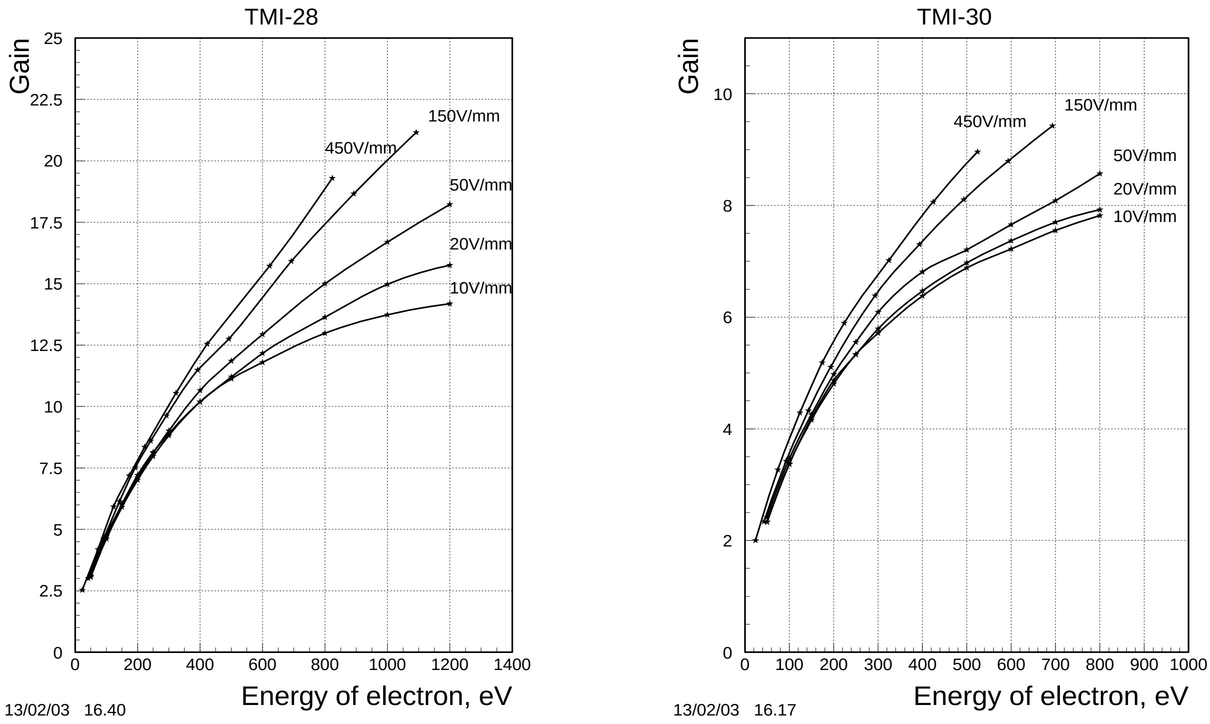


Fig. 8. Dependencies of a reflected dynode gain on secondary electron energy and an electric field between this dynode and anode for TMI-28 (left) and TMI-30 (right).

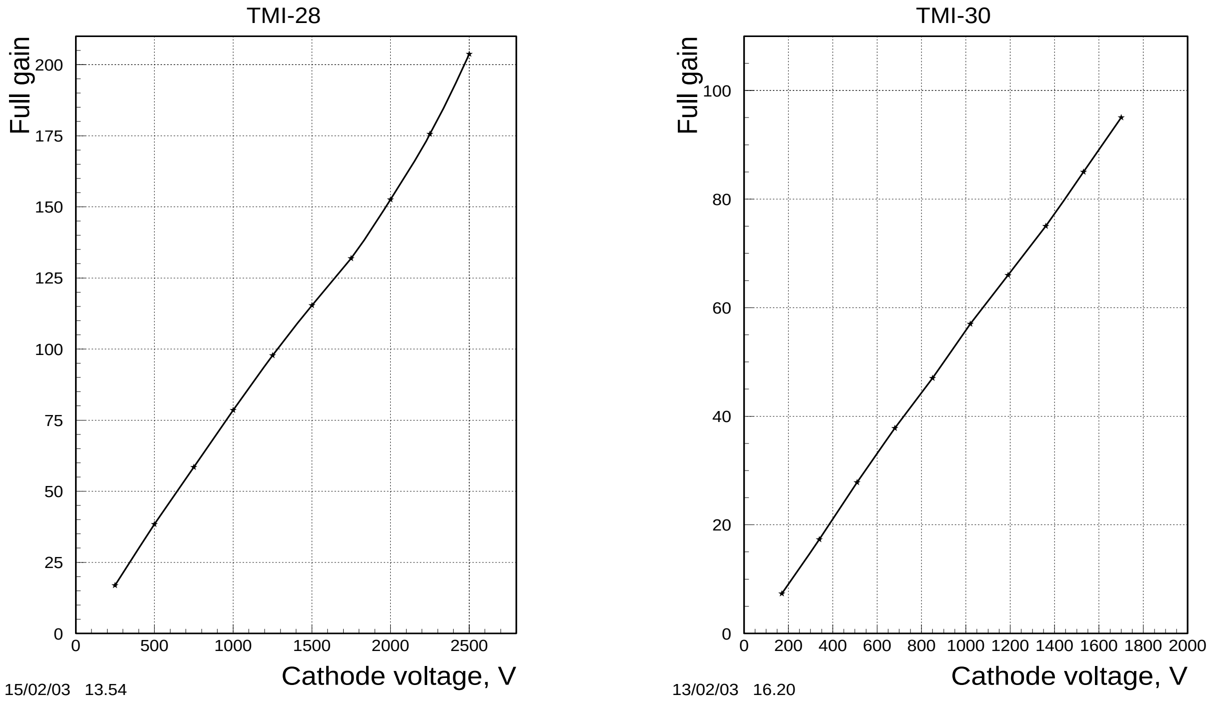


Fig. 9. Dependencies of a phototetrode's gain for TMI-28 (left) and TMI-30 (right) under the proportional increase of power supply voltages.

4. Some evaluation of CMS Forward ECAL energy resolution taking into account a use of the designed phototetrodes

Phototetrodes with a gain around 100–200 were produced and we hope to increase the gain even more. It is interesting to look at what kind of gain we can get in case of Endcup ECAL using the designed phototetrodes.

It seems that magnetic field resistance of these tetrodes should be comparable to the resistance of fine mesh triodes since shoot through dynode represents itself as a flat conductive film and therefore a secondary emission of this shoot through dynode should be weakly sensitive (at a photocathode level) to the magnetic field.

Let's make an evaluation of the dependence of CMS Endcup ECAL energy resolution on the gain of photoreceivers.

For example, from the paper [6] follows, that

$$\frac{\sigma}{E}=\frac{a}{\sqrt{E}}\oplus\frac{\sigma_n}{E}\oplus C,$$

where a – stochastic term, σ_n – noise, C – constant term.

Photostatistic contribution of a stochastic term under the use of VPT with typical photocathode quantum efficiency of $\varepsilon = 0.15$ received from LED monitoring – $a_{\text{phe}} = (3.5\pm0.55)\%$.

For σ_{noise}/GeV and C it is possible to take into account the values from this paper: the value $\sigma_n = 0.53$ and C=0.5%.

The contribution from noise ~1/G, where G is a photoreceiver gain, therefore this contribution can be represented as

$$noise=\frac{0.53}{E\cdot\frac{G}{G_0}},$$

where G_0=10 is a typical phototriode gain.

Let's look at the dependence of the sum ($\sigma_{\text{tot/E}}$) of photostatistics (the basic contribution to the stochastic term) and noise terms contributions from energy for the cases of G=10, G=50, G=100, G=150 and G=200.

Таблица 2.

E (GeV)	1	10	50	100	500	1000
$\sigma_{\text{tot/E}}$ (G=10)	$5.31\cdot10^{-1}$	$5.41\cdot10^{-2}$	$11.7\cdot10^{-3}$	$6.35\cdot10^{-3}$	$1.89\cdot10^{-3}$	$1.23\cdot10^{-3}$
$\sigma_{\text{tot/E}}$ (G=50)	$1.12\cdot10^{-1}$	$1.53\cdot10^{-2}$	$5.38\cdot10^{-3}$	$3.66\cdot10^{-3}$	$1.58\cdot10^{-3}$	$1.11\cdot10^{-3}$
$\sigma_{\text{tot/E}}$ (G=100)	$0.635\cdot10^{-1}$	$1.23\cdot10^{-2}$	$5.06\cdot10^{-3}$	$3.54\cdot10^{-3}$	$1.57\cdot10^{-3}$	$1.108\cdot10^{-3}$
$\sigma_{\text{tot/E}}$ (G=150)	$0.497\cdot10^{-1}$	$1.14\cdot10^{-2}$	$4{,}98\cdot10^{-3}$	$3.51\cdot10^{-3}$	$1.57\cdot10^{-3}$	$1.107\cdot10^{-3}$
$\sigma_{\text{tot/E}}$ (G=200)	$0.439\cdot10^{-1}$	$1.14\cdot10^{-2}$	$4{,}98\cdot10^{-3}$	$3.51\cdot10^{-3}$	$1.56\cdot10^{-3}$	$1.107\cdot10^{-3}$

We see, that up to 100 GeV the variant of $\varepsilon = 0.15$; $G \geq 100$ essentially better than $\varepsilon = 0.15$; G=10 variant from **Table 2**. At the same time it is known that at energies more than 100 GeV photostatistics and noise contributions become less than other contributions.

Conclusion

1. The technology designed at IHEP and MELZ permits the production of the radiation hard phototriodes with a gain of 30–50.

2. Designed phototetrodes with shoot through dynodes have a gain up to 200 and there is the possibility to increase this value.

3. There is the real possibility to create the single channel and the multichannel photomultipliers with shoot through dynodes which can operate in any practical magnetic fields (more than 4 T).

4. In such photomultipliers dispersion of flight time between photocathode and first dynode, consecutive shoot through dynodes, reflective dynode and fine mesh anode will be not more than 10 psec under gaps between them around 1mm. Therefore, for example, in the case of 6-stage PMT by amplification more 10^6, total dispersion of electron flight time will be less than 35 psec, what at two orders of value less than dispersion of flight time of usual fast photomultipliers (what determines duration of one-electron pulses at anode) and at one order of value less than time dispersion of photoelectrons in their cathode cameras.

The use of PMT with shoot through dynodes will possibly permit greatly raising the resolution of flight-time spectrometers on the base of scintillating and Cherenkov counters.

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Received 9 June, 2004

С.А. Белянченко, В.В. Бреховских, В.А. Дятченко и др.
Фототриоды и фототетроды с высоким усилением.

Оригинал-макет подготовлен авторами.

Подписано к печати 10.06.2004. Формат 60 × 84/8. Офсетная печать.
Печ.л. 1. Уч.– изд.л. 0,8. Тираж 60. Заказ 284. Индекс 3649.

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ПРЕПРИНТ 2004-23, ИФВЭ, 2004